University of Nevada

Reno

Stratigraphy and Structure of the Paleozoic Rocks in the Rush Creek Drainage, Northern Ritter Range Pendant, California.

A Thesis submitted in partial fulfillment of the requirements for the degree of Master of Science

by

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ABSTRACT

Detailed geologic mapping in the Rush Creek drainage, in the northern part of the Ritter Range pendant, Sierra Nevada Range, reveals a stratigraphic sequence of Paleozoic rocks previously unknown and herein defined as the Rush Creek sequence.

The Rush Creek sequence most probably represents lower Paleozoic (?) miogeoclinal strata deformed during the Antler orogeny. These rocks possibly correlate with the transitional assemblage of lower Paleozoic rocks in Nevada. The Mesozoic metavolcanic Koip sequence overlies the Paleozoic Rush Creek sequence with a sheared angular unconformity.

Two major deformational events affected the metamorphic rocks of the Rush Creek drainage. D1 deformation formed a series of northeast trending folds during the mid-Paleozoic Antler orogeny. D2 deformation formed northwest trending main phase F2 folds and S2 cleavages and late phase small scale folds and crenulations during the Late-Jurassic Nevadan orogeny.

The Gem Lake shear zone is a sequence of highly deformed and mylonitic rocks making a ductile shear zone between the Rush Creek sequence and the overlying Koip sequence. Planer zones of high strain are possibly D1 and D2 deformation thrust faults.

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INTRODUCTION

Purpose

The purpose of this investigation is to study in detail the stratigraphy and structure of the Paleozoic rocks in the Northern Ritter Range pendant and to relate this geology to the regional stratigraphy and structure.

Previous to this study the Paleozoic rocks in the Northern Ritter Range pendant were poorly understood because mappable units were not identified. This was due to the complicated nature of the rocks and the difficult terrain. Thus there was no clear synthesis of geologic age, structural style or stratigraphy of the rocks.

During this study a new stratigraphic sequence was identified. Inferences drawn from the results of this study suggest the rocks in this part of the eastern Sierra may be related to the Paleozoic miogeocline in Nevada. Additionally, structural data collected during this study has clarified the deformational history of the area. These results enable comparisons to be made with stratigraphic and structural data to the east in Nevada.

Location

The study area is located in the Rush Creek drainage, one of several eastwest trending, glaciated canyons in the Northern Ritter Range pendant.

The area lies in the south-central part of the Mono Craters 15° Quadrangle about 10 km east of Yosemite National Park and 20 km southwest of Mono Lake.

The field area is reached by hiking several kilometers up the Rush Creek Trail from a trail head located at Silver Lake along the June Lake Loop, Highway 158. U.S. Highway 395 serves as the primary artery for the region. (see Index map, fig. 1 and fig. 2)

Methods

During an initial ten day reconnaissance in the summer of 1983 the basic stratigraphic and structural pattern was observed. It became apparent that to unravel the complicated arrangement of folded strata, a detailed study in a limited area would be required. In the summer of 1984 seventy field days were spent mapping in detail the Paleozoic metasedimentary rocks within the limits of the Rush Creek drainage.

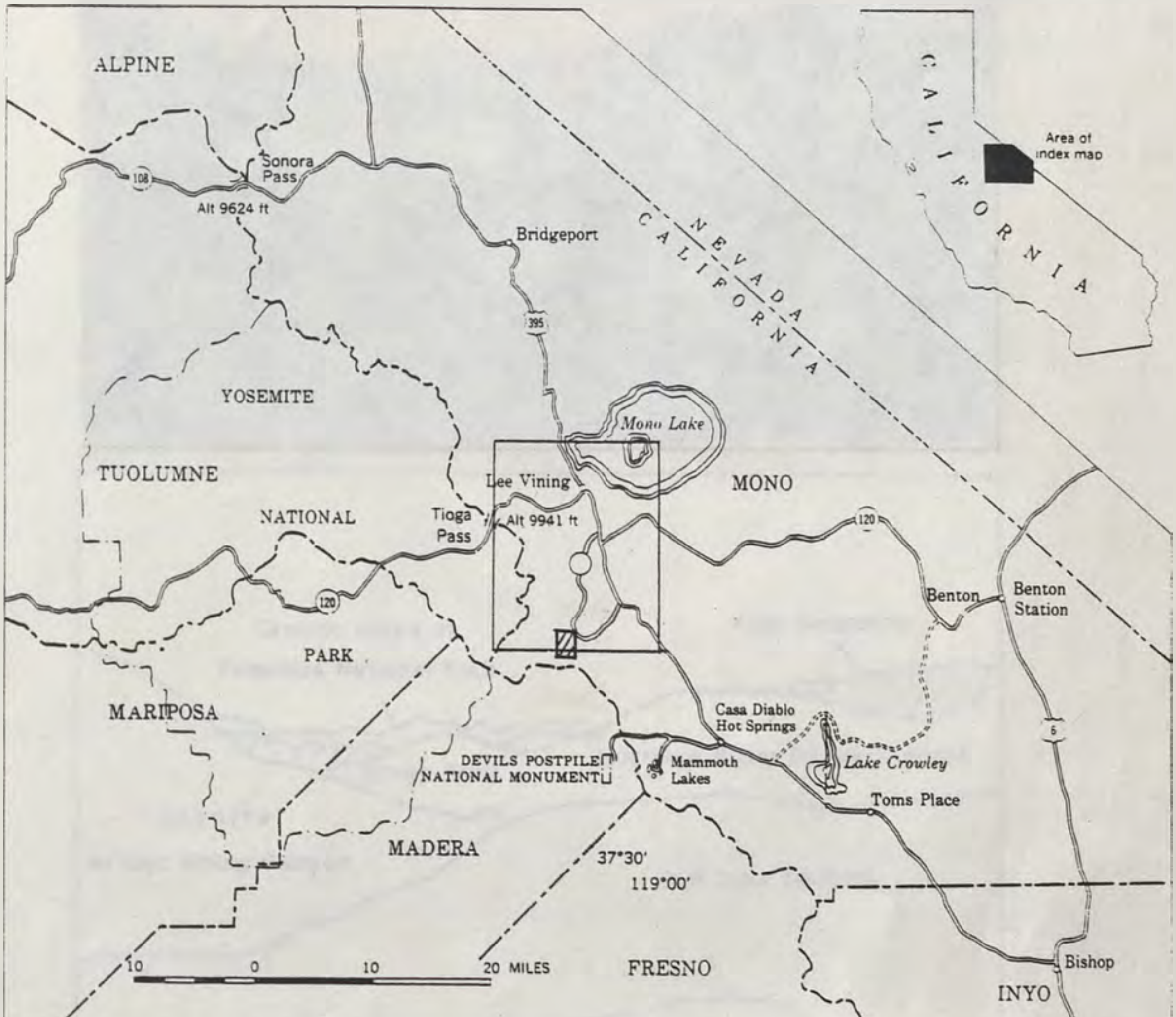

Fig. 1 Index map showing location of the Mono Craters quadrangle, Mono County, California. Study area (small box diagonal ruled at bottom of quadrangle) is located in the Rush Creek Drainage in the Northern Ritter Range pendant. (Modifide from Rinehart and Ross (1964)).

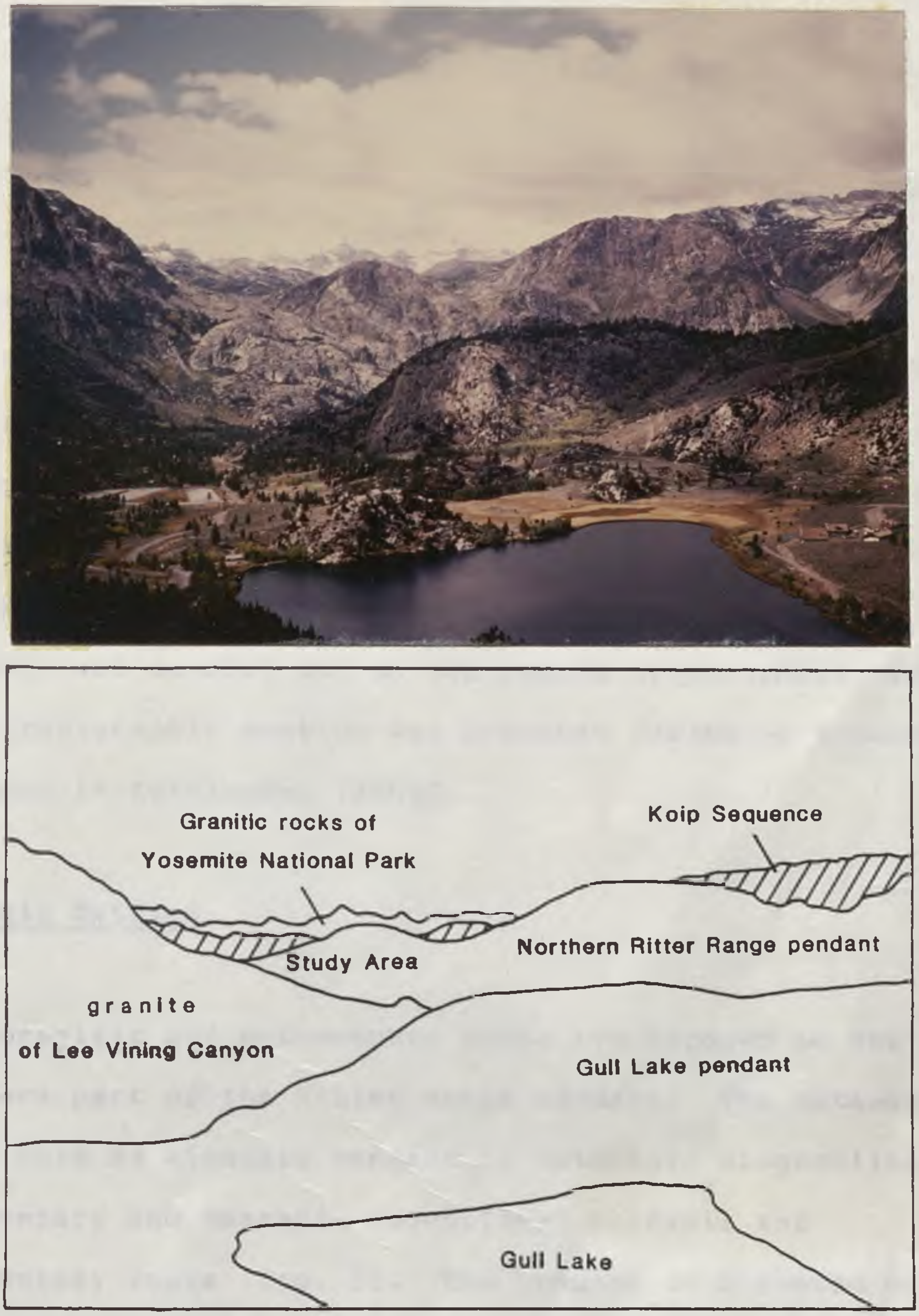

Fig. 2 Photograph and line drawing of the east face of the Sierra Nevada range. The study area lies in the Rush Creek drainage and within the Northern Ritter Range pendant. The broad light colored stripe across the study area is unit 5 of the Rush Creek sequence. Photograph taken from the June Lake area looking west across the Gull Lake pendant.

Outcrop mapping was carried out on an enlarged color aerial photograph with an approximate scale of 1:3800. Structural attitudes were measured with the Brunton Compass. Stratigraphic thickness was determined with the Jacob-staff or estimated from the aerial photograph.

Rock samples were collected from each stratigraphic unit and analyzed in the laboratory. This work included petrographic studies of twenty five thin sections. Eighteen rock samples were dissolved in either acetic, hydrofloric, or formic acids to separate microfossils. Microprobe analysis was carried out on one sample of phosphatic chert. The stratigraphic section was prepared following procedures outlined in Kottlowski (1965).

Geologic Setting

Granitic and metamorphic rocks are exposed in the northern part of the Ritter Range pendant. The metamorphic rocks form an elongate pendant of Paleozoic miogeoclinal sedimentary and Mesozoic eugeoclinal volcanic and sedimentary rocks (fig. 3). The pendant is bordered on the east by Triassic granitic rocks and on the west by Cretaceous granitic rocks.

To the east in north-central Nevada, Paleozoic geology is dominated by the northeast trending Paleozoic miogeocline (Burchfiel and Davis, 1972, 1975). The major tectonic

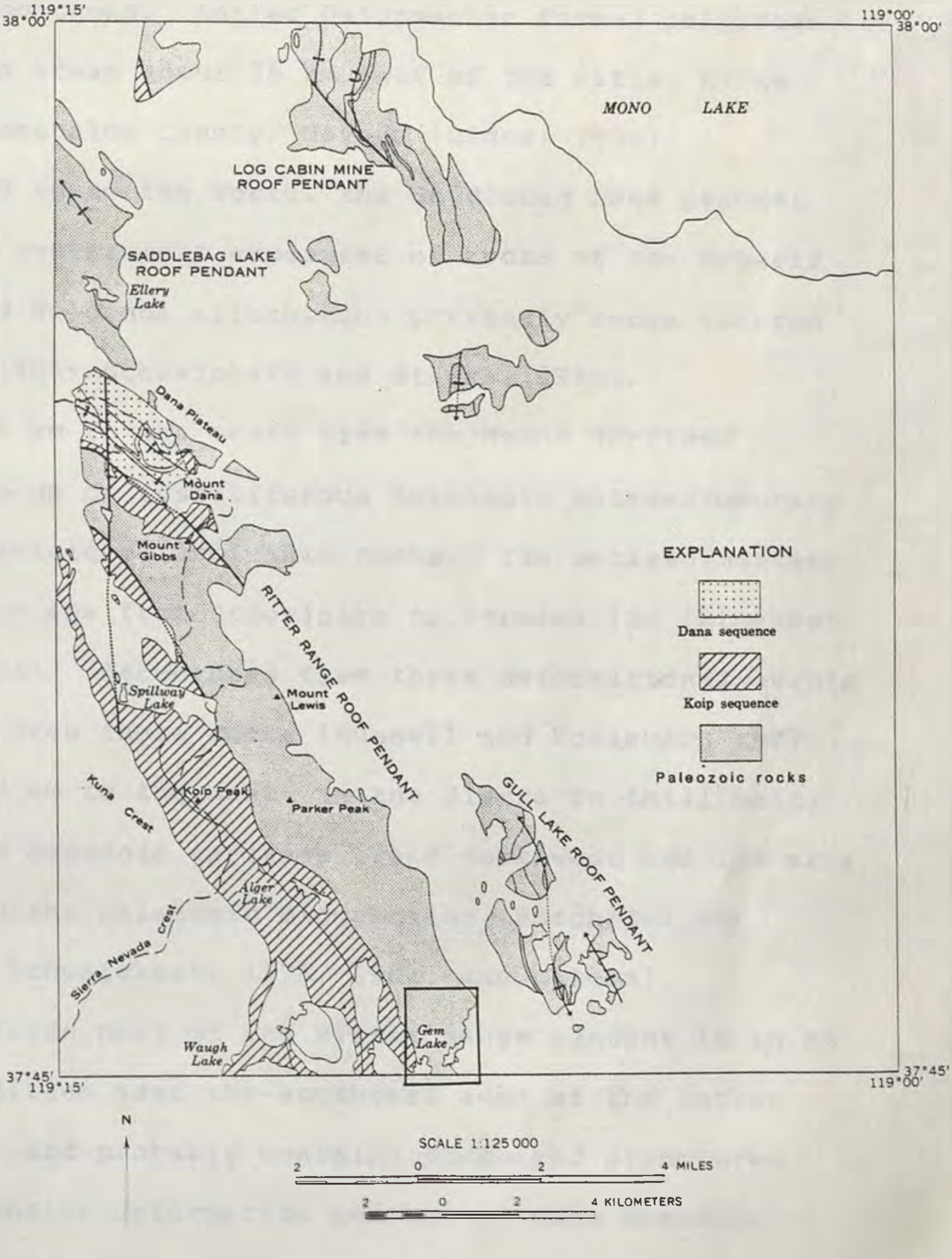

Fig. 3 Map showing distribution of prebatholith rocks and the study area (box) in the Mono Craters quadrangle. Modified from Kistler (1966b).

features are the mid-Paleozoic Antler and Early Triassic Sonoma orogenic belts comprised of the Roberts Mountains and Golconda allochthons. Antler deformation formed polyphase structures in areas about 55 km east of the Ritter Range pendant in Esmeralda County, Nevada (Oldow, 1984).

About 25 km to the North, the Saddlebag Lake pendant contains the westernmost exposures of rocks of the Roberts Mountains and Golconda allochthons presently known (Lahren and others, 1984; Schweickert and others, 1984).

About 35 km to the south lies the Mount Morrison pendant, made up of fossiliferous Paleozoic metasedimentary rocks and Mesozoic metavolcanic rocks. The metasedimentary rocks range in age from Ordovician to Permian (?) (Rinehart and Ross, 1964). Structures from three deformational events are reported from these rocks (Russell and Nokleberg 1977)

About 45 km to the west, in the Sierra foothill belt, Paleozoic and Mesozoic terranes trend northwest and lie at a high angle to the Paleozoic miogeocline (Burchfiel and Davis, 1972; Schweickert, 1976, 1981; and others).

The northern part of the Ritter Range pendant is in an important position near the southeast edge of the Antler orogenic belt and probably contains rocks and structures involved in Antler deformation and one or more Mesozoic deformational events.

Previous Work

Putnam (1938) mapped and described the metamorphic and igneous rocks in the Gull Lake Pendant, about 3 km east of the field area.

Rinehart and Ross (1964) examined rocks in the Gull Lake Pendant and correlated the strata with Ordovician and Silurian (?) strata in the Mount Morrison Pendant about 35 km to the south.

Kistler (1960, 1966b) mapped the Paleozoic rocks in the Rush Creek drainage at the scale of 1:62,500, described their structure and suggested their age to be late Paleozoic.

Huber and Rinehart (1965) mapped the Spooky Meadow area of the Devils Postpile Quadrangle just south of the study area. They concluded that the metamorphic rocks, which are a continuation of those in the Rush Creek drainage, are similar to upper and lower Paleozoic rocks in the Mount Morrison Pendant.

Tobisch and Fiske (1976) mapped and documented structure within Mesozoic metavolcanic rocks of the Koip sequence along the western portion of the Ritter Range pendant west of Gem Lake.

Tobisch and Fiske (1982) studied Paleozoic and Mesozoic rocks in the Ritter Range several km southwest of the field area. They suggested that northwest-trending folds and cleavages were formed by multiple and parallel deformations as old as early Mesozoic and as young as mid-Cretaceous.

Brook and others (1974) examined the contact between Paleozoic rocks and Mesozoic rocks in the Ritter Range and Saddlebag Lake pendant and suggested the structure is a folded angular unconformity. They also argued that northwest trending folds tighten from east to west and interpreted these northwest folds as the result of two phases of deformation. Ages of the deformations were considered as post Sonoma orogeny (post late Triassic).

Kistler and Nokleberg (1979) described the stratigraphic relationships of the metasedimentary rocks in the Ritter Range and Gull Lake pendants, presented new fossil data, and interpreted the rocks as Pennsylvanian and Permian (?).

Kistler and Swanson (1981) proposed radiometric ages for the metamorphosed Mesozoic volcanic rocks in the east-central Sierra Nevada Range based upon whole rock Rb-Sr and U-Pb zircon dates.

PETROLOGY

Terminology

Terms used to classify each rock type follow those established by Rinehart and Ross (1964) for the Paleozoic rocks in the Mount Morrison Pendant 35 Km to the south. The composition, textures and metamorphism of the Paleozoic rocks in the Rush Creek drainage are similar to those of rocks described by Rinehart and Ross. Although the rocks are very similar, direct correlation with rocks in the Mount Morrison Pendant is considered conjectural at this time.

Methodology

Twenty five thin sections from the metamorphic and the igneous rocks were examined with a petrographic microscope, and the mineral percentages for each specimen were estimated. Identification of feldspars was made on the basis of twinning and relief. All minerals including calc-silicate and accessory minerals were identified using standard methods outlined by Kerr (1959).

Samples were taken to assist in understanding the general lithologic characteristics of each rock unit, but they were not intended for a detailed petrographic study. The least altered rocks that would represent the premetamorphic rock types were sampled. Although none of the units was traced to unmetamorphosed rock, certain interpretations of the parent material were made from relict mineralogy, textures and primary structures.

Metamorphism

Detailed analysis of metamorphism was not within the scope of this study. Previous workers, Bateman (1963), Rinehart and Ross (1964), Kistler (1966b), Kerrick (1970), and others established a metamorphic history for the local Sierrian pendants. Their analysis has shown that the Paleozoic rocks experienced a complex metamorphic history. Bateman (1963) suggested at least three episodes of metamorphism: the first was regional metamorphism; the second was regional and thermal metamorphism; and the third was thermal metamorphism. Locally the Ritter Range pendant probably experienced even more episodes of metamorphism. The major events which probably produced the metamorphism are: the mid-Paleozoic Antler orogeny; the late Triassic phase of batholithic intrusions; the late Jurassic Nevadan orogeny; and the late Cretaceous phase of batholithic intrusions.

Mineral assemblages in general fall within the albite-epidote hornfels and hornblende hornfels facies in pelitic rocks, with the mineral assemblage quartz + feldspar (plagioclase and/or orthoclase) + actinolite (tremolite) + biotite + muscovite + magnetite + epidote.

The rocks show two textures: (1) a well-defined planar schistosity defined by mica and amphibole and (2) a hornfelsic texture defined by nondirectional granoblastic minerals. Commonly the hornfelsic texture overprints the earlier planar fabric.

General Lithology

The rocks in the Paleozoic section of the Rush Creek drainage are metamorphosed fine-grained sedimentary rocks. The majority of the section is composed of very fine-grained quartz-rich hornfels including calc-silicate hornfels, chert (commonly phosphatic), marble, pelitic hornfels, slate and lesser amounts of coarser grained quartzite. Under conditions of contact metamorphism the impure argillaceous and silty rocks were transformed into aggregates of metamorphic minerals. Quartz and calcite remained relatively stable. Relict clastic grains are preserved in siltstone and sandstone and the clastic grains define sedimentary structures such as graded bedding and crossbedding.

Seven basic rock types recognized in the Rush Creek drainage are outlined below. The parent material and the metamorphic product are included.

(1) Silty and impure carbonate rocks that contained various amounts of siliceous, calcareous and dolomitic material have been metamorphosed to calc-silicate hornfels.

(2) Quartz-rich feldspathic siltstone has been metamorphosed to siliceous hornfels.

(3) Argillaceous rocks have been metamorphosed to slate and pelitic hornfels.

(4) Chert has remained chemically unaltered but in most cases has been recrystallized.

(5) Relatively pure limestone and dolomite have been metamorphosed to marble.

(6) Sandy limestone has been metamorphosed to sandy marble.

(7) Quartzofeldspathic sandstone has been metamorphosed to quartzite.

Rock descriptions

These seven basic rock types are recognised on the basis of their average mineral composition. The diagram in fig (4) shows the approximate average composition of the different metasedimentary rocks in terms of their most abundant minerals. Rinehart and Ross (1964) stressed that the diagram only provides a graphic means of portraying the principal quantitative distinctions among the different rock types and should not be viewed as a classification chart. The seven basic rock types are described below.

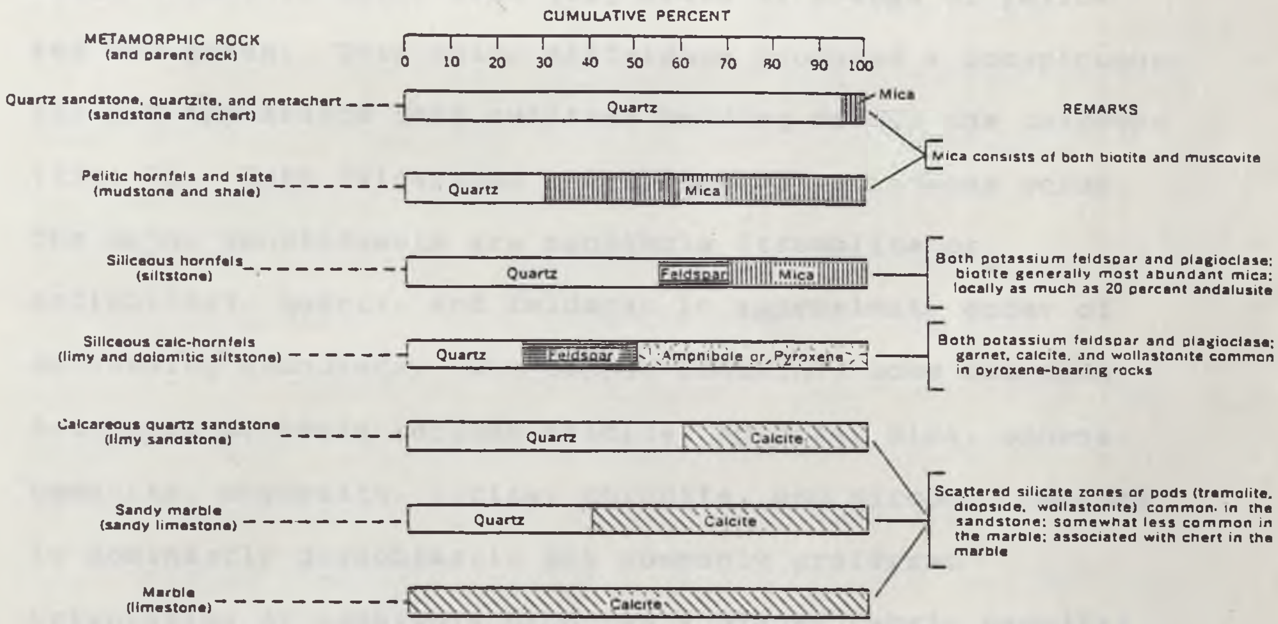

Fig. 4 Diagram showing the approximate average mineralogic composition of the metasedimentary rocks in terms of the essential minerals. Taken from Rinehart and Ross (1964).

Calc-silicate hornfels

Calc-silicate hornfels is typically microgranular, laminated to very thinly-bedded, and weathered surfaces range widely in color from gray-black to shades of yellow, red and green. This color difference produces a conspicuous striped appearance that outlines bedding across the outcrops (fig. 7). Both calcareous and siliceous variations occur. The major constituents are amphibole (tremolite or actinolite), quartz, and feldspar in approximate order of decreasing abundance. One sample contained some diopside. Accessory minerals include calcite, epidote, mica, sphene, hematite, magnetite, pyrite, chlorite, and zircon. Texture is dominantly granoblastic but commonly preferred orientation of amphibole produces a planar fabric parallel to bedding. Grain size ranges from .01 mm to .4 mm with the average size about .04 mm. The amphiboles have serrated edges and commonly form large porphyroblasts set in a dense, finer grained matrix. Aggregates of quartz are preferentially distributed in individual layers and define bedding. Detrital sand grains of quartz are distinguished by their subangular shape, larger grain size than most of the minerals, and random distribution.

Siliceous hornfels

A siliceous rock is considered siliceous hornfels when it contains substantial amounts of mica and feldspar. Siliceous hornfels is microgranular, laminated to very thinly bedded. Weathered surfaces are dark red-brown and fresh surfaces range from light to dark gray. Bedding is faintly visible on weathered surfaces. The major constituents are quartz, muscovite, feldspar (orthoclase ?) and opaque material. Accessory minerals include calcite, idocrase (?), hematite, pyrite, sphene, apatite, zircon, and epidote. Grain size averages about .03 mm. The dominant texture is granoblastic but mica commonly shows a well-defined planar orientation. Relict clastic texture is commonly preserved, and is characterized by subangular quartz grains set in a fine-grained matrix of quartz, feldspar, mica and opaques. Bedding is defined by differing quantities of quartz and opaque material in individual layers.

Metachert

Metachert is a microgranular, granoblastic, fine-grained mosaic of quartz. Accessory minerals include minor apatite, opaques, mica, amphibole (tremolite - actinolite), epidote, pyrite, and calcite. Metachert has a vitreous luster on fresh surfaces and is generally black. Commonly, white phosphate streaks and nodules are aligned parallel to bedding. In thin section a rock is classified as metachert when quartz exceeds 80 % of the mineral composition. Generally chert is impure and grades into siliceous hornfels. In the field, chert is distinguished from siliceous hornfels by its vitreous luster while siliceous hornfels has a dull luster.

Light-gray phosphate occurs in chert as nodules, lenses and streaks. In general, spherical nodules range in size from 4 to 10 cm in chert beds 8 to 25 cm thick (see fig. 8).

Electron microprobe analyses indicate that the phosphate nodules are composed of fluorapatite and quartz. The phosphate is very fine-grained and intergrown with quartz. The sample is relatively high in Ca and F compared to other marine florapatites but the rock is deformed and has been metamorphosed (Varga 1985, written communication). Phosphate in thin section occurs as microcrystalline masses.

Slate and pelitic hornfels

Slate and pelitic hornfels are distinguished in thin section from siliceous hornfels arbitrarily on the basis of the abundance of muscovite and average grain size. They have well oriented abundant microscopic mica and typically are extremely fine-grained (average about 0.001 mm). Major minerals are muscovite, quartz and opaques (carbonaceous material ?). Accessory minerals include hematite, magnetite, pyrite, epidote, chlorite and apatite. Bedding is generally not visible in the field but in thin section bedding is commonly defined by mica and quartz rich layers and by concentrations of opaque material. Pelitic hornfels is relatively soft and can be scratched with a knife. In comparison, slate differs from pelitic hornfels in two ways; (1) pelitic hornfels is softer and (2) slate shows well-developed cleavage and pelitic hornfels generally does not.

Quartzite

Quartzite is light gray and is composed predominantly of very fine-grained quartz, about 5 to 10 % feldspar (orthoclase or microcline and plagioclase(?)) and minor lithic fragments. Accessory minerals include epidote, actinolite, tourmaline and zircon. Quartz grains commonly show incipient polygonization by weak undulating extinction of individual grains. Calcite is isolated within cleavage planes and rarely occurs in the matrix. One sample contained a lithic fragment with intergrowths of quartz and feldspar that resemble graphic granite. The quartzite is poorly sorted with the larger quartz grains size about 1 to 2 mm in a very fine matrix about 0.005 mm to 0.05. The quartz grains are rounded to well rounded indicating the transport distance was substantial. Feldspar is consistently finer grained, about 0.5 to 1 mm The metamorphic minerals such as epidote probably were the product of metamorphism. The protolith was probably a lithic arenite (subarkose) composed of coarser grained quartz in a limy matrix of finer grained quartz, feldspar, and rock fragments.

Marble

Marble ranges in color from white to light gray to dark blush-gray. The marble is generally fine-grained, but large calcite crystals occur in certain areas due to contact metamorphic recrystallization. In thin section marble is composed of cryptocrystalline calcite or dolomite with an average grain size between 0.01 to 0.04 mm. Accessory minerals include diopside, tremolite, pyrite, muscovite and sometimes abundant opaques. Commonly marble contains abundant sand grains that are fine to medium grained, well-rounded and appear to have frosted surfaces.

STRATIGRAPHY

Introduction

The prebatholithic rocks in the Rush Creek drainage are divided into two sequences on the basis of their stratigraphic and structural characteristics. These are the Rush Creek sequence and the Koip sequence. The Rush Creek sequence is a newly defined unit named herein. Definitions of these sequences are outlined below.

(1) The Rush Creek sequence represents lower Paleozoic (?) miogeoclinal strata deformed during the Antler orogeny. These rocks may be correlative with the transitional assemblage of lower Paleozoic rocks in Nevada.

(2) The Koip Sequence lies with a sheared angular unconformity upon the Rush Creek sequence. The Koip sequence is made up of volcanic and sedimentary strata deposited within an Andean type marginal arc in Late Triassic to Early Jurassic time.

Description of Units

Rush Creek sequence

Nine stratigraphic units that make up the Rush Creek sequence have a combined estimated thickness of 820 meters. Unit one is designated the oldest and unit nine is designated the youngest. The top and the bottom of the sequence are unknown.

Reference sections for units 1 through 4 in the Rush Creek sequence are located north of Agnew Lake, and reference sections for units 5 through 9 are located along the map cross section A-A'. The locations of the reference sections are identified on the geologic map (Plate I) by a box enclosing the representative number of each unit (eg. [5]). The stratigraphic section (Plate III) as been designed to be used in conjunction with the text. A generalized stratigraphic section is provided in the text for easy reference (see fig. 5).

The map units in the Rush Creek sequence shown on the geologic map and the stratigraphic section are numbered below and are grouped by their basic rock type.

(1) Map units 1,4, and 8 are composed of calc-silicate hornfels.

				PROTOLITH	METAMORPHIC ROCK
MESOZOIC	KOIP SEQUENCE	not measured	KOIP	VOLCANOCLASTIC SEDIMENTS, MINOR L.S., AND VOLCANIC FLOWS	METASEDIMENTS AND METAVOLCANICS
		TOP NOT EXPOSED		ANGULAR UNCONFORMITY	(SHEARED)
LOWER (?) PALEOZOIC	RUSH CREEK SEQUENCE	120M	UNIT 9	CHERT/PELITE	METACHERT/PELITIC HORNFELS
		100M	UNIT 8	IMPURE LIMESTONE/ DOLOMITE	CALCSILICATE HORNFELS
		38M	UNIT 7	L.S./CHERT	MARBLE/METACHERT
		90M	UNIT 6	CHERT/SHALE/IMPURE L.S.-DOL.	METACHERT/SLATE/ CALCSILICATE HORNFELS
		65M	UNIT 5	L.S./CHERT/S.S.	MARBLE/METACHERT/ QUARTZITE
		42M	UNIT 4	IMPURE L.S.-DOL.	CALCSILICATE HORNFELS
		36M	UNIT 3	L.S./CHERT	MARBLE/METACHERT
		105M	UNIT 2	CHERT	METACHERT
		22M	UNIT 1	IMPURE L.S.-DOL.	CALCSILICATE HORNFELS
		BASE NOT EXPOSED			
		35M	UNIT 1'	CHT/IMPURE L.S.-DOL.	METACHT/CALCSILICATE

Fig. 5 Generalized stratigraphic section of the Paleozoic rocks in the Rush Creek drainage, Northern Ritter Range pendant, California.

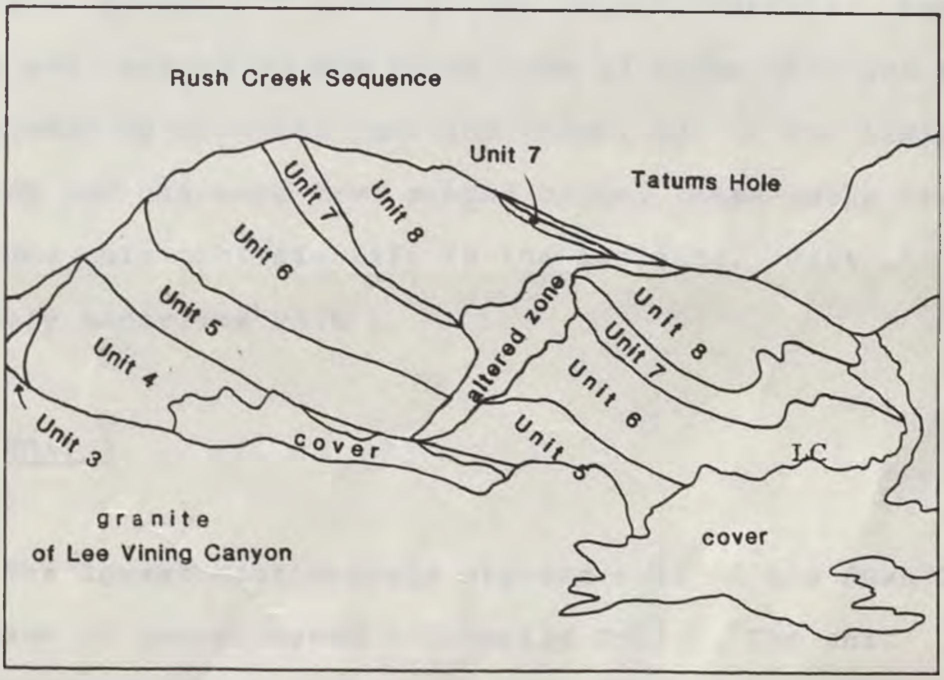

Fig. 6 Profile view of the Rush Creek sequence looking west and close up of fig. 2. Elevation of peak at center is 9550 feet (2865m) and Rush Creek (at water fall) below is 8000 feet (2400m). Width of photograph is about 1 kilometer. Bedding strikes northeast and dips away from the observer.

(2) Map units 2,6,and 9 are composed of siliceous hornfels, chert, slate and pelitic hornfels.

(3) Map units 3 and 7 are composed of dark gray marble, with equal or lesser amounts of interbedded chert, siliceous hornfels, slate and pelitic hornfels.

(4) Map unit 5 is composed of light gray marble, chert, sileceous hornfels and quartzite.

<u>Unit 1'</u>

Unit 1' is composed of well bedded calc-silicate hornfels, phosphatic chert and siliceous hornfels. These rocks are exposed on the south side of Agnew Lake and are surrounded by granitic rock and water. Due to the limited outcrop and distance from mapped units, these rocks are included only provisionally in the sequence. Unit 1' probably underlies unit 1.

<u>Unit 1</u>

The lowest continuously exposed unit of the Rush Creek sequence is herein named informally Unit 1. The unit consists of a relatively homogeneous, thinly-bedded, microgranular calc-silicate hornfels. Beds alternate from gray to black to shades of red and pale green. At a distance outcrops appear light tan and striped, due to slight variations in mineral composition between individual beds (fig. 7). Bedding in Unit 1 is parallel to the contact with Unit 2. The contact with Unit 2 trends northeast, is sharp, and shows a color contrast between light tan rocks of Unit 1 and the overlying black cherty rocks of Unit 2.

The unit is well exposed on the north shore of Agnew Lake and forms a prominent boss that juts out into the lake (see geologic map, Plate I). The upper part of this outcrop can be observed along the Rush Creek trail. Elsewhere the unit is bordered by slope wash, vegetation or Agnew Lake.

At the southwest tip of Agnew Lake, Unit 1 is inferred to be in contact with Unit 2. The upper part of Unit 1 is exposed for 180 meters along a contact that trends southwest and is eventually lost in ground cover and cliffs bordering the unmapped Spooky Meadow area. This outcrop has been displaced from the stratigraphically continuous exposures of Unit 1 in the ridge north of Agnew Lake by a major fault.

Unit 2

The rocks of Unit 2 consist chiefly of dark-gray to black thinly-bedded chert, thin- to thick-bedded siliceous hornfels and subordinate thin- to thick-bedded slate. Commonly bedding is not conspicuous, but on cliff faces, continuous sequences with faint bedding can be observed. The bedding is continuous even though individual beds cannot

Fig. 7 Weathered surface of calc-silicate hornfels showing conspicuous striped appearence owing to the contrast in color of alternating beds. Unit 1 located north of Agnew Lake.

be traced more than 10 to 30 meters. Weathering produces a rusty veneer that conceals the bedding. Phosphate streaks and nodules, while generally rare, are abundant near the top of the unit. In many cases, white phosphate defines bedding in otherwise structureless black cherty rocks (fig. 8).

Thickness is inferred from one locality, because elsewhere the base is not exposed. This locality is where Unit 1, previously described, is in contact with Unit 2 on the ridge north of Agnew Lake. The estimated thickness is 105 meters. Considerable deformation in this area makes the estimated thickness only approximate.

Unit 2 is extensively exposed within the pendant and forms the exposed base for most of the sequence. It conformably overlies Unit 1. Sparse outcrops of Unit 2 can be easily examined at the base of Agnew Dam along Rush Creek and just to the west along the Rush Creek trail. Most exposures of unit 2 are inaccessible and form cliffs along the south facing slope of the drainage.

Unit 3

Unit 3 is an assemblage of thinly-bedded chert, siliceous hornfels, slate, and abundant thinly-bedded marble. The color of the unit is a distinctive iridescent bluish-black, similar to the color gun-metal-blue. Phosphatic streaks and nodules are locally abundant in

Fig. 8 Bedded chert with white phosphatic streaks and nodules. Faint, near vertical lines are the traces of northwest S2 cleavage. Unit 3 located north of Agnew lake. The elongate phosphate streak in the center of the photograph is about 18 cm long.

cherty layers (fig. 8). Marble is subordinate to the siliceous rocks and is generally a dense, dark bluish-gray rock. Some of the marble beds are sandy. Bedding in marble ranges from very thin, 2 to 7 cm, to a few beds up to 30 cm. The siliceous rocks are thinly bedded and are black to dark gray on fresh surfaces and weather rust-red. Chert is characterized by a greasy luster and common phosphatic streaks and nodules. Siliceous hornfels and slate are distinguished from metachert by their dull surface, thicker beds and style of cleavage.

The reference section of Unit 3, as with most of the outcrops in this unit, is in very rugged terrain and reached only by climbing steep cliffs. For this reason a complete section could not be traversed. The unit is best observed from a distance due to markedly contrasting colors of the overlying and underlying units. Unit 2 grades upward into Unit 3 as marble increases in abundance. From a distance the most visible change between Unit 3 and the underlying Unit 2 is color. The rusty brown and black of Unit 2 changes to a characteristic iridescent blue-black of Unit 3. Unit 3 is exposed mid-way up the ridge north of Agnew Lake and strikes generally northeast for nearly 1200 meters. To the west, beyond a major northwest trending fault, discontinuous outcrops in intensely deformed rocks are interpreted as belonging to Unit 3 and these define a large scale synform.

Unit 4

Unit 4 is composed of calc-silicate hornfels that is indistinguishable from units 1 and 8. The color at a distance is typically shades of tan and the unit has a characteristic striped appearance. Fresh surfaces are light olive green due to the abundant amphibole (actinolite-tremolite). The rocks are well bedded and contain relatively homogeneous, thinly-bedded strata. The calc-silicate along the base of Unit 4 overlies marble rich rocks of Unit 3. Along this contact is a 10 meter thick reaction zone stained rust-red and having a baked appearance. This reaction zone is commonly observed within the pendant where calc-silicate hornfels is in contact with marble. This suggests that during contact metamorphism reaction occurred at contacts between dissimilar rock types (see fig 9).

The unit is about 43 meters thick and crops out almost continuously along a northeast strike for about 900 meters. The western exposures are structurally more complex and form elongate bosses that strike in a northwest direction.

The reference locality for Unit 4 is just north of the north-east end of Agnew Lake. The unit is well exposed but mostly inaccessible except in the easternmost part of the

Fig. 9 Showing contact between units 3 and 4. Note the typical outcrop style of Unit 4, calc-silicate hornfels, which is resistent to glacial scouring and forms an elongated boss and the undermining of the underlying Unit 3, marble and chert. The darker base of Unit 4 shows a red reaction stain from interaction with marble of Unit 3 during metamorphism.

sequence. About 240 meters downstream from Agnew Dam a traverse up a steep talus slope will provide marginal exposures. Units 2 and 3 are less resistant than Unit 4 and therefore Unit 4 forms ledges that protrude outward and away from the slopes forming steep cliff faces. The best exposures can be reached by climbing down narrow ravines from the top of the ridge.

Unit 5

Unit 5 is the most distinctive unit in the Rush Creek sequence. Viewed from a distance, the unit forms a broad, light gray to white stripe across the darker slopes (fig. 2 and 6). The unit shows up especially well on color aerial photographs.

The dominant rock types in the unit are light gray marble, dark gray to black cherty rocks and light gray quartzite. Phosphatic material is rare in Unit 5. The marble is dolomitic in part and is divided into three subunits by 2-5 meter thick chert layers. This relationship is shown in figures 10 and 11.

The chert units that separate the carbonate layers form continuous and uniform marker beds that can be traced for 450 meters without appreciable disruption as illustrated in figures 6 and 10. It is noteworthy that alternation of chert with marble occurs only in this unit. The chert

Fig. 10 Shows continuous and uniform stratigraphy displayed by the light colored marker unit, Unit 5.

Fig. 11 Close-up view of unit 5.

marker layers in Unit 5 are useful for correlation where the structure is complex in the western portion of the sequence.

A 9 meter thick chert layer forms the basal part of Unit 5. The chert is interbedded with siliceous hornfels and slate. Siliceous hornfels and slate typically weather rusty red-brown.

The lower marble subunit is about 14 meters thick, is thinly-bedded and contains nodules and irregular lenticular bodies of chert. The nodules are lumpy ellipsoids about 30 cm in length and are flattened irregularly in the plane of bedding. Most of the nodules are scattered and randomly spaced, while others are concentrated along bedding planes. The nodules occur in discrete units of marble or siliceous marble (fig. 12). The 23 meters of overlying carbonate rocks have little chert. Many marble beds have a conspicuous speckled appearance from coarse, well-rounded quartz sand grains. Some beds are very sandy but throughout the carbonate beds quartz sand grains are subordinate to carbonate minerals.

In the middle of Unit 5 is a 9 meter thick feldspathic quartzite (fig 13). This is the only quartzite in the entire sequence. The makeup of this quartzite is described in a previous section under rock descriptions (see quartzite p. 18). In general the quartzite is light gray and is composed of fine-grained quartz, and lesser amounts of feldspar and lithic fragments. Calcite is

Fig. 12 Bedded marble and chert nodules in Unit 5.

Fig. 13 Massive quartzite in Unit 5.

isolated within cleavage planes and rarely occurs in the matrix. The grains are poorly sorted, rounded to well-rounded and range is size from about 1 to 2 mm to about 0.005 to 0.05 mm in the matrix. One thin section contained a lithic fragment that resemble graphic granite. The protolith was probably a lithic arenite (subarkose).

Unit 5 is exposed continuously for about 750 meters and discontinuously for another 450 meters in the more structurally complex areas to the west. At the reference section it is 65 meters thick. It is easily accessible from the Rush Creek Trail where the trail crosses the tramway for the second time, about 450 meters down stream from Agnew Dam (plate 1, geologic map).

Unit 6

Unit 6 is 90 meters thick and consists of lower, middle and upper subunits that are not subdivided on the geologic map. The lower subunit is predominantly chert. Phosphatic streaks and nodules are abundant close to the lower contact with Unit 5 and progressively decrease in abundance 9-15 meters above the contact. The middle subunit contains calc-silicate hornfels, siliceous hornfels and lesser amounts of chert. Phosphate is rare or absent. A few very thinly-bedded carbonate beds are interbedded with calc-silicate. A 9-10 meter layer of light tan and interbedded cream-white calc-silicate rocks that mark the middle part of this unit can be traced for 600 meters. The upper subunit consists of equal amounts of black chert, siliceous hornfels, and lighter tan or brown to green calc-silicate hornfels. Phosphate in the upper subdivision is rare and was observed only in a few beds.

Unit 7

Unit 7 is composed of interbedded cherty rocks and marble. Unit 7 is about 38 meters thick where it is least disturbed structurally. It forms a continuous and uniform unit for only 100 meters at the reference section. To the west, the unit is intruded and deformed almost beyond recognition. A few remnants and the overall stratigraphic order of the sequences provide evidence that the unit was originally continuous (fig. 6).

Dolomitic marble and marble are abundant in Unit 7 and make up at least 50 percent of the rock. Most of the marble is dark blue-gray, fine-grained, and dense. It weathers to a fluted and pitted, "elephant skin" textured surface. A few carbonate beds contain variable amounts of quartz sand and one bed 4 meters from the base of the unit contain chert pebbles. Calc-silicate, a minor constituent, is mainly light gray-green, but one bed has an anomalous gray-pink color. A few thick beds at the top of the unit are almost entirely made up of white, coarse-grained calcite.

In general, the siliceous rocks of unit 7 are mainly chert with subordinate amounts of siliceous hornfels and a minor amount of slate. Phosphate streaks and nodules are uncommon but traces are present in a few cherty beds.

Well-preserved thinly-bedded strata characterize the reference section located in the eastern part of the pendant (fig. 14 and 15).

The basal contact with Unit 6 is gradational. At the contact, predominantly siliceous rock at the top of Unit 6 is interbedded with very thinly-bedded, dark gray, dense dolomitic marble.

Unit 8

Unit 8 is predominantly calc-silicate hornfels with very thin- to thin-bedding. The beds are multicolored from gray to olive-green to black and various shades of red, brown, orange and yellow. Some of the layers are cherty and a few layers are tan carbonate rock (fig. 16).

A 6-9 meter wide red-brown stain discolors the calc-silicate beds and marks the lower contact with Unit 7. The reaction zone occurs all along the exposed contact with the carbonate rich rocks of Unit 7 and does not occur within the body of Unit 8.

Fig. 14 Looking northeast along strike of Unit 7 in the eastern area of the Rush Creek sequence. Note the base of Unit 8 is marked by a reddish reaction zone and contrasts with white calcite rich beds of the underlying Unit 7.

Fig. 15 Close-up of planar bedding of Unit 7 looking west. Beds are composed of marble and chert.

Fig. 16 Bedding in Unit 8, calc-silicate hornfels. Light colored beds are rich in carbonate minerals and show ductile deformation as pinch and swell structures. Dark beds are rich in siliceous and calc-silicate minerals and reacted as competent or rigid layers during deformation. Faint S2 cleavage transects northeast trending bedding. Note the refraction of cleavage in different layers defined by change in dip angle.

The true thickness of Unit 8 is difficult to determine accurately due to internal folding. An estimated thickness is 100 meters. The unit is continuously exposed along the top of the ridge over a strike length of about 500 meters. The unit is truncated by a fault in a narrow saddle separating relatively continuous and uniform units to the east and more deformed units to the west. Outcrops in Tatums Hole are probably correlative and a continuation of this unit.

Unit 9

In the map area, Unit 9 is the highest stratigraphic unit preserved in the Rush Creek sequence. The unit is composed of a monotonous and massive pelitic hornfels and slate. Much of the outcrop is stained a brick red-brown color. The rock is microgranular, black, and generally structureless. Faint laminations and rare bedding planes were observed in a few locations. Where bedding is pronounced it is parallel to the trends of the lower units.

The base of Unit 9 is conformable with Unit 8 and the top is not exposed. The total exposed thickness is about 120 meters. Similar rocks that crop out on the north side of Tatum's Hole suggest that this unit and the Rush Creek sequence as a whole extends northward.

Rocks of the Gem Lake shear zone

Between the overlying Koip sequence and the coherent strata of the Rush Creek sequence is a zone of highly strained rocks. These rocks are named herein the Gem Lake shear zone and are very similar in composition to those in the Rush Creek sequence and are probably correlative. Because the bedding is transposed and internally sheared the rocks could not be directly assigned to any of the nine units identified in the Rush Creek sequence.

The Gem Lake shear zone is composed of laterally continuous but incompletely defined units of slate, chert, calc-silicate, marble interlayered with chert, and massive sandy marble. Black pelitic rocks are strongly cleaved and appear similar to fissile shale. Lighter colored gray silty rocks show a planar fabric and little fissility. Cherty rocks are laminated to very thinly-layered. Marble forms very thin layers alternating with chert and to a lesser degree with pelite. Massive varieties of sandy marble contain 1-2 cm chert nodules and quartz sand grains. For examples of these rocks see figures 32 through 36 in the section on structure.

One of the principal differences between the rocks within Gem Lake shear zone and the rocks within the Rush Creek sequence is that layering is consistently much thinner and less continuous in the Gem Lake shear zone. The layering is generally very thin to laminated, ranging between 1-3 cm thick. Additionally, layering consistently trends northwest in the shear zone at a high angle to the northeast trend of bedding in the eastern part of the Rush Creek sequence.

The shear zone is well exposed on the south side of Gem Lake. On the north side of the lake the same units occur also. The pelitic and cherty rocks along the western boundary with the Koip sequence are thicker to the northwest. The Gem Lake shear zone is discussed in more detail in the section on structure.

<u>Relict Sedimentary Structures</u>

All the rocks of the pendant have been multiply deformed and metamorphosed and in most cases sedimentary textures have been obliterated. However, relict quartz grains and layers of recrystallized minerals locally define graded bedding and cross bedding and indicate the younging direction of the strata. Load casts and small scour and fill channels were observed as well. Tops are directed to the northwest in the northeast trending strata. The best location for observing relic sedimentary structures is within Unit 8 along the ridge crest between the Rush Creek drainage and Tatum's Hole. This location is reached by hiking north about 500 meters from the Rush Creek trail where it enters the Minarets Wilderness boundary near Gem Lake. At the outcrop, cross bedding in calc-silicate hornfels indicates the strata are locally overturned to the east. Scour and fill channels showing cross bedding occur about 10 meters north of the outcrop.

Load casts occur in Unit 6 along the base of a cliff face, right side of photo marked "LC" in figure 6, and is reached by hiking about 150 meters up a talus slope from the point where the trail makes its lowest crossing of the tramway.

Depositional Setting

Protoliths of the Rush Creek sequence consisted of chert, impure limestone, mudstone, siltstone, limestone, and minor sandstone, deposited in a marine environment. The fine-grained and well-bedded sediments were probably deposited in a low-energy environment in open water of the outer shelf. The sediments received terrigenous detritus during the entire depositional cycle. Calc-silicate hornfels and marble consistently contain scattered rounded, and frosted quartz sand grains. A 9 meter thick, massive, coarse to fine grained feldspathic sandstone layer in Unit 5 has rare lithic fragments of graphic granite. Considering these sedimentary characteristics the Rush Creek sequence probably was deposited along a stable continental margin.

Correlation and Age Constraints

New data from this study indicate the Rush Creek sequence was deformed prior to the deposition of the Koip sequence,about 230 m.y. ago. As discussed later in the structural section, this deformation probably occurred during the mid-Paleozoic Antler orogeny, which implies that the Rush Creek sequence predates the Antler orogeny and is probably early Paleozoic in age. These early structures deform the rocks in the Gull Lake pendant as well, suggesting rocks there also are lower Paleozoic (R.W. Kistler personal communication, 1984).

Lahren and others, (1984); Schweickert and others (1984) have proposed that the Saddlebag Lake pendant, about 25 km to the north, contains the westernmost exposures of rocks of the Roberts Mountains and Golconda allochthons presently known. This indicates that Paleozoic rocks of the Rush Creek sequence, which lie structurally below the rocks in the Saddlebag Lake pendant, may either be part of the Roberts Mountains allochthon or autochthonous to the Roberts Mountains thrust.

In the Northern Ritter Range pendant chert contains nodules, lenses and streaks of phosphate. Phosphatic chert of similar nature occurs within Ordovician/Silurian and Upper Devonian rocks of the northern Sierra Nevada range (Varga, 1982) and in Ordovician to Lower Mississippian rocks of the Roberts Mountain allochthon in central Nevada (Coles and Snyder, 1985). Importantly the presense of phosphate suggests an age between Cambrian and Lower Mississipian.

The characteristic rock types of the Rush Creek sequence are interbedded chert and limestone, with lesser amounts of siltstone and quartzite. These lithologies compare closely with the lower part of the Ordovician Palmetto Formation and the Upper Cambrian Emigant Formation described by Albers and Stewart (1972) for rocks in Esmeralda County, Nevada, about 65 km to the east. In the Miller Mountain area in Esmeralda county, Nevada, Oldow (1984) also described similar lithologies for Antler deformed rocks which he called the Palmetto complex. Such rocks are part of the lower Paleozoic transitional assemblage outlined by Stewart (1980, p20, Table 1).

The interpretation favored here, therefore, is that the Rush Creek sequence represents part of the Cambrian-Ordovician transitional assemblage and has a paleogeographic link to the lower Paleozoic miogeocline in Nevada.

Koip sequence

The Koip sequence was not studied in detail for this project. Based on published work it is composed of metavolcanic and metasedimentary rocks consisting of basalt flows, andesite to rhyodacite tuffs, limestone, and graywacke (Kistler 1960, 1966a and b; Brook and others, 1974). Kistler (1960) noted that sedimentary structures indicate tops face southwest and indicate the sequence is younger than the underlying Rush Creek sequence. Locally along the contact with the Rush Creek sequence, the Koip sequence is made up of lithic wacke with lenses of matrix supported pebbly conglomerate (fig 17 and 37). The lithologic makeup is completely different from that of the underlying Rush Creek sequence.

Based on whole rock Rb-Sr dating, the lower part of the Koip sequence south of latitude 38° is about 237 $\pm$ 11 M.Y. (Kistler and Swanson 1981) but U/Pb zircon ages from samples south of Gem Lake are 186 to 214 M.Y., and a Lower Jurassic fossil was identified near Thousand Island Lake (Fiske and Tobisch 1978). The age of the lower part of the Koip sequence in the Rush Creek drainage is probably about 230 M.Y. (R.W. Kistler, personal communication)

Igneous Rocks

Granite of Lee Vining Canyon

The major igneous body in the field area is the granite of Lee Vining Canyon, which forms the eastern border of the

Fig. 17 A matrix supported pebbly conglomerate at base of the Koip sequence. Strong foliation trends about N 30 W, dips 85 southwest and reflects (S2) main-phase foliation. Large lenticular clast is about 6 cm in length. Located near the north shore of Gem Lake.

pendant and truncates the stratigraphy of the Rush Creek sequence (see geologic map, Plate 1 and fig. 14). This pluton has yielded a whole-rock Rb-Sr isochron age of 212 $\pm$ 8 M.Y. (Kistler 1966b) and is correlated with the Triassic Scheelite sequence of older plutonic rocks in the eastern Sierra Nevada (Stern et al, 1981). Intrusion of the granite of Lee Vining Canyon occurred after D1 deformation and before D2 deformation.

The granite is medium- to coarse-grained and consists of quartz, orthoclase, plagioclase, biotite, and minor hornblende in order of decreasing relative abundance. On fresh surfaces orthoclase is euhedral, pink, and forms large phenocrysts giving the rock a porphyritic texture. Commonly, the the rock shows a weathered and granular textured surface.

To reclassify the granitic rocks of Lee Vining Canyon according to modern nomenclature, modal compositions of eleven samples analyzed by Kistler (1960, Tables 5 and 6, p. 93 and 94) were averaged. The average modal mineral composition is quartz 37%, K feldspar 34%, plagioclase (An 22-38) 31%, biotite 4.0%, hornblende 0.3%, and accessories 0.7%. According to the IUGS classification system the rock is granite and not quartz monzonite as formerly named.

The contact between the granite and metamorphic rocks is commonly sharp, discordant and dips steeply away from the metamorphic rocks. Pleistocene glaciers have reduced most of the contact area to topographic lows or benches. Consequently, slope wash, talus and till cover most of the contact. Younger dikes further complicate the contact as they apparently intruded along the contact when they intersected it.

Intrusive dikes and sills

Three generations of dikes and sills occur in the Rush Creek drainage. The oldest is pre D1 deformation, another is post D1 and pre D2 deformation, and the youngest is post D2 deformation. The sources of these dikes is unknown. Possibly the second generation dikes may have been magmas that erupted volcanic rocks of the Koip sequence and the granite of Lee Vining Canyon.

The dikes were not studied in detail and much of their structural relationships are not known. The dikes were not differentiated on the geologic map but their relative ages are mentioned because of their potential importance in dating the deformation in future work. Pre D1 dikes have only tentatively been identified because structural relationships are complex and their exposure is limited. Dikes that predate D2 deformation are certain because they contain a strong foliation parallel to S2 foliation in the metamorphic rocks. Dikes that postdate D2 crosscut all D1 and D2 structures and do not contain foliation.

All the igneous intrusions show some degree of contact metamorphism evident by the alteration of crystals and epidotization. Because of the profuse number of intrusins in the field area many dikes and sills were not drawn on the geologic map.

Pre Dl Intrusions

Only two dikes that predate Dl were observed and their exposure was limited, and for these reasons they were not plotted on the geologic map. They are green to black, fine-grained dikes that are strongly epidotized. Primary minerals are no longer visible and the contacts with the metamorphic rocks are blurred. The parent rock for these dikes is mafic, possibly basalt or gabbro. Thickness is about 0.5 meters or less. The dikes have not been observed in contact with the plutonic rocks. Fl folds appear to deform the dikes.

The best example of a pre-Dl dike crops out near the reference section for Unit 8 on the crest of the ridge between Rush Creek and Tatums hole (see location on the geologic map, plate I). This dike is recognizable for only 8 to 10 meters, trends N 30 E and dips near vertical. The dike cuts at a low angle across the nose of a large Fl fold, and shows small amplitude short wavelength folds that trend about N 50 E and N 30 W.

Putnam (1938) observed dikes older than the granite of Lee Vining Canyon in the Gull Lake pendant 3 km east. He noted they have a recrystallized appearance and suggested they had been contaminated by calc-silicate hornfels during metamorphism. Putnam suggested the protolith of these dikes was diorite or gabbro.

Pre D2 Intrusions

The second intrusive episode is marked by both granitic and granodioritic dikes and sills. The second generation of dikes occurred after D1 deformation and before D2 deformation. The outstanding feature of the dikes and sills is that they are foliated with a strong planar fabric parallel to the S2 slaty cleavage, suggesting the fabric developed during D2 deformation. Two such dikes extend sinuously in a northwest direction across the Rush Creek drainage. The dikes are plotted on the geologic map between Gem Lake dam and Agnew Lake. The foliation trends about N 30 W and dips about 55 southwest.

The granitic dikes are made up of quartz, plagioclase, K-feldspar (orthoclase), biotite, and minor hornblende. Their general similarity in composition to the granite of Lee Vining Canyon suggests an affinity between the two. One granitic dike that crops out just north of Gem Lake dam ranges from 10 to 20 meters thick, trends northwest and contains a strong foliation that trends about N 25 W.

Granodiorite porphyry dikes contain phenocrysts of plagioclase, quartz, biotite and muscovite set in a matrix of quartz and feldspar. They originally may have been emplaced as intrusions related to volcanic activity which formed the adjacent Koip Sequence.

Post F2 Intrusions

Younger intrusions are marked by their fresh appearance, crosscutting relationships and lack of tectonic fabric. One sample contains phenocrysts of plagioclase (andesine), quartz (20 - 25%), and biotite set in a dense matrix of plagioclase and quartz, and is best classified as granodiorite or quartz-diorite. Accessory minerals include sericite, magnetite, chlorite and epidote. Commonly dark gray to black, fine-grained dikes accompany the porphyritic dikes as later intrusions that used the same path.

The dikes are located in all areas of the pendant and are generally discordant. Commonly the post D2 dikes follow the joint systems and faults and trend northwest or northeast. Their thickness varies greatly and some are less than a meter thick but as a rule are 3 to 10 meters thick. The best example of a post D2 dike is a thick granodiorite porphyry dike that cuts the granite and the metamorphic rocks located directly below Agnew Lake dam.

Unconformities

The Rush Creek sequence is separated from the overlying Koip sequence by an angular unconformity that is sheared and faulted in the Rush Creek drainage based on data in this report (fig 18). In the Mount Morison pendant, along a probable continuation of this contact, Morgan and Rankin (1972) made a similar interpretation. In contrast other workers have argued that the unconformity is not faulted (Kistler 1966b; Brook and others 1974)). It is, however, a regional contact in the eastern Sierra Nevada that separates Paleozoic metasedimentary rocks from Mesozoic metavolcanic rocks.

Due to ductile shearing along the angular unconformity between the Koip and the Rush Creek sequence, layering in both sequences is transposed parallel to the contact. However, the general strike of the underlying Rush Creek sequence is at a high angle to the contact. Physical evidence that the contact was originally an unconformity is a pebbly a conglomerate at the base of the Koip sequence. Kistler (1966b) and Brook and others, (1974) have suggested these pebbles and clasts were derived from the Paleozoic rocks that underlie the Koip sequence during a hiatus representing the Sonoma Orogeny. The basal conglomerate is discontinuous and in most areas pebbles are scarce. Generally, the basal part of the Koip sequence is pebbly

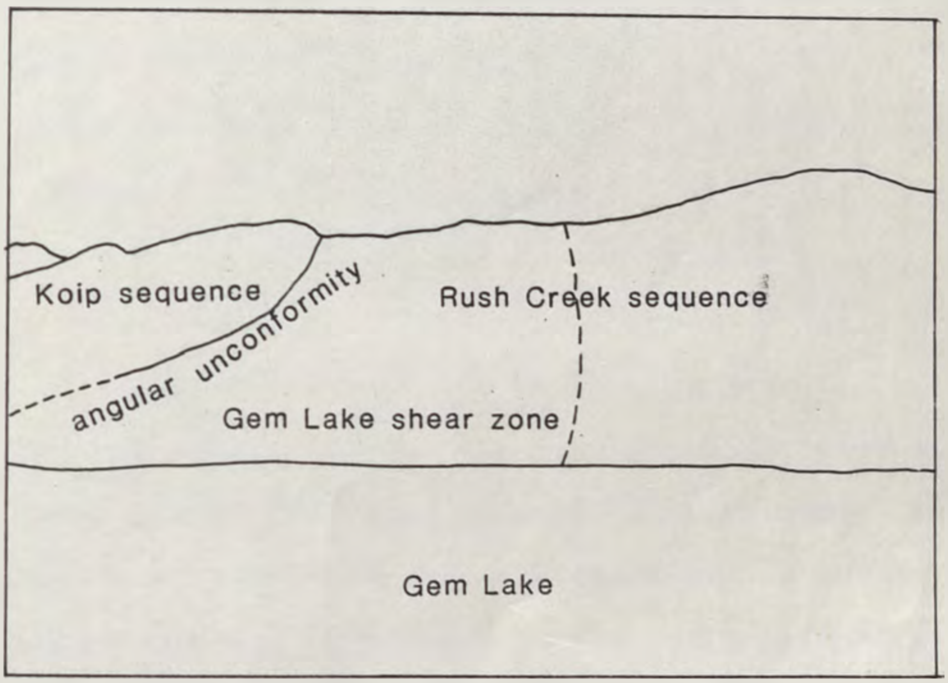

Fig. 18 View of the north side of Gem Lake showing the contact between the Paleozoic Rush Creek sequence and the overlying Mesozoic Koip sequence. Scale: Gem Lake elevation 9020 feet (2706 meters), High point on ridge 9760 feet (2928 meters).

sandstone with local matrix-supported pebbly conglomerate (fig 17). Upsection in the Koip conglomerate grades into a finer grained, sandy lithic wacke with minor amounts of pebbles (fig 37).

STRUCTURE

Introduction

Two major deformational events affected the metamorphic rocks of the Rush Creek drainage. Structural elements related to these events are distinguished by significantly different orientations and styles. D1 deformation formed a series of large northeast trending F1 folds that involve the Rush Creek sequence. D2 structures are superimposed upon D1 structures. D2 deformation resulted in a series of ubiquitous northwest trending F2 folds and S2 cleavages. It is noteworthy that D2 structures are weakly developed in the east and progressively more strongly developed to the west. In addition, D2 deformation produced an initial main phase of structures and a late phase of structures.

Several narrow planar northwest trending zones of intense D2 deformation dissect less deformed areas and are distributed across the Rush Creek sequence. Evidence is fragmentary but the data suggests that D2 deformation produced northeast directed imbricate thrusts and that these thrusts may in part be reactivated older D1 thrusts. If correct, then northeast D1 thrust planes were transposed to a northwest trend during D2 deformation.

In the Paleozoic rocks, structural domains are named from east to west. The Rush Creek sequence is comprised of domains I, II, III, and IV, the east, middle, west areas, and the Gem Lake shear zone respectively. The Mesozoic rocks of the Koip sequence make up domain V. The domain boundaries have been drawn somewhat arbitrarily although they approximate locations where the structural complexity of D2 structures changes (see fig. 19 and Plate IV, structural data inset map). Domains are discussed in more detail under D2 structures in this section.

Plate IV outlines the results of structural measurements from all five domains. Attitudes of cleavage, fold axial surfaces, and other structural elements were plotted on Schmidt equal-area nets. The diagrams were constructed according to the methods outlined by Ragan (1973, p. 91 - 120) and Compton (1962, p. 317 - 318). The writer suggests that plate IV be used in conjunction with the text. Numerous references to the stereographic projections and tables are used in this section to illustrate trends and to compare overprinting relationships.

D1 Deformation

Distribution of D1 Structures

Northeast trending D1 deformation structures occur only in the Rush Creek sequence. Major F1 folds are common in the eastern part of the sequence, in domain I, and are

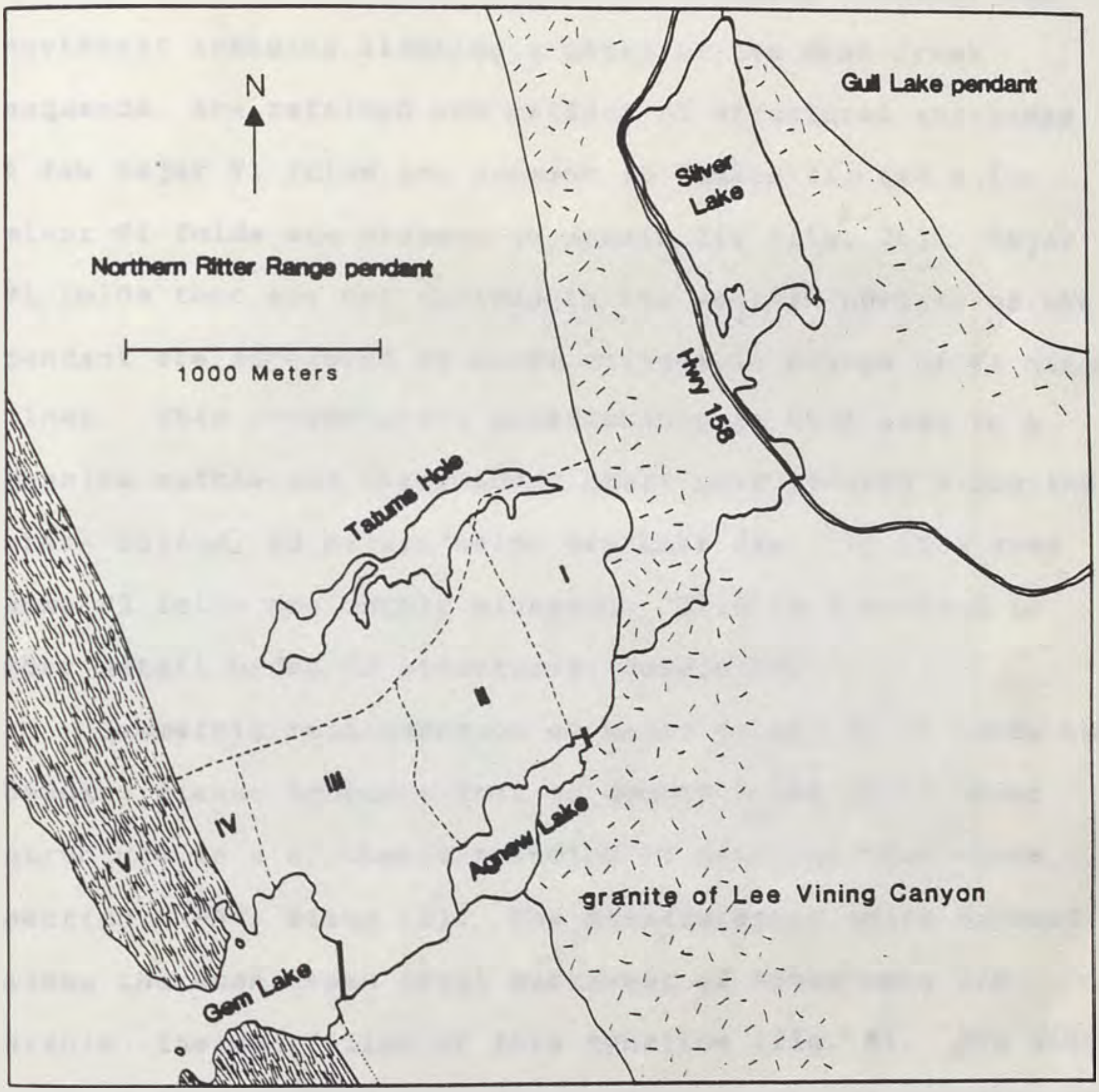

Fig. 19 Sketch map showing structural domains across the Northern Ritter Range pendant. Domains I through IV represent the Rush Creek sequence and domain V is the Koip sequence.

obscured by later D2 deformation to the west. In the western part of the area, northeast trending bedding, and northeast trending lithologic units of the Rush Creek sequence, are refolded and reflect F2 structural attitudes. A few major F1 folds are present in domain II, and a few minor F1 folds are present in domain III (fig. 26). Major F1 folds that are not obvious in the western portion of the pendant are suggested by local changes in plunge of F2 hinge lines. This overprinting relationship is best seen in a massive marble and interbedded chert unit located along the creek bottom, 60 meters below Gem Lake dam. In this area some F2 folds are doubly plunging. This is discussed in more detail under F2 structures, domain II.

Geometric relationships of major folds, minor folds and bedding planes indicate that in domain 1 the first order structure is a northeast trending F1 syncline (see cross section A -A', Plate II). The stratigraphic units exposed along the Rush Creek trail northwest of Agnew Lake lie within the south limb of this syncline (fig. 6). The hinge area of this synform is corrugated by northeast trending F1 folds (fig 20). The north limb is inferred by asymmetry of parasitic folds although the limb is not exposed. This first-order syncline may actually be a second-order parasitic fold on the south limb of a much larger syncline with a northeast trending axial surface trace through Tatum's Hole. This interpretation is based on similar

Fig. 20 Oblique view of northeast trending F1 folds in Unit 7, east area of the Rush Creek sequence. Folds plunge about 60° away from the observer. Note Unit 8, calc-silicate hornfels in core of fold. Close up of fig. 6.

lithology and structure observed in cliffs on the ridge north of Tatum's Hole. However, this area was not mapped and the interpretation is not yet confirmed.

Description of D1 Structures

Major F1 folds are especially well exposed in calc-silicate hornfels of Unit 8 in the eastern part of domain 1. In addition, in early morning light, dramatic exposures of F1 folds in Unit 7 are visible in a cliff face that can be viewed from the June Lake Loop Highway looking up the Rush Creek Drainage (Figs. 6 and 20). The fold closures in the cliff face repeat on the ridge top and form a series of nearly upright anticlines and synclines with steeply dipping axial surfaces that strike N 35 - 55° E and with fold hingelines that plunge 37 - 56° toward azimuth 215 - 232° (Plate IV, stereonets B and C). The F1 axial surfaces and hinge lines have variable attitudes due to superimposition of F2 folds. The details of F2 overprinting relationships are discussed under the heading of F2 folds, domain 1.

Typical major F1 folds in calc-silicate rocks are tight to close, predominantly symmetrical, similar and also parallel, have complex hinges, curved axial surfaces, variably plunging hinge lines, curvi-planar limbs and are commonly transected by S2 cleavage (fig. 21).

Fig. 21 Complex F1 fold hinge in Calc-silicate hornfels of Unit 8 located in eastern part of domain I. Layers show contrasting change in orthogonal thickness with some layers forming parallel profiles and others forming similar profiles. Note S2 cleavage displaces beds on left limb.

Complex hinges like the one shown in figure 21 are the result of contrasting mechanical behavior of individual layers during deformation. The more siliceous or cherty layers have responded rigidly and the more calcareous layers have responded ductilely. The difference in competence explains the coexistence of parallel and similar profiles of individual layers in the same fold. While most F1 folds have similar fold geometry, parallel fold profiles occur where marble and chert predominate.

Minor F1 folds or parasitic folds are not common but a few were observed in the east part of the sequence along the cross section A - A'. Along the south limb of a large northeast trending syncline parasitic folds exhibit a southward sense of vergence and along the north limb parasitic folds exhibit a northward sense of vergence. This asymmetry of minor folds supports the interpretation that a large scale syncline is the local first order structure.

S1 Cleavage

S1 cleavage is generally absent in the calc-silicate and carbonate units which are the predominant lithologies exposed in domain I. Even the cherty layers in the calc-silicate hornfels usually have no obvious cleavage. However, S1 spaced cleavage is well-developed in phosphatic chert of Unit 2 in Domain II northwest of Agnew Lake, where its orientation is axial planar to a fairly large, open, and parallel F1 fold whose axial surface strikes about N 47° E and dips 60° northwest. In poorly defined bedding 30 meters south of the above fold, S1 cleavage has an average strike of N 30° E and a dip of about 70° SE. In detail, cleavage is divergent in the syncline and dips away from the axial surface. No displacement was noted along the cleavage planes. Another rare occurrence of S1 cleavage in the Rush Creek sequence is in Domain III below Gem Lake Dam (fig. 26).

Age constraints on D1 deformation

Age of the D1 deformation is constrained as pre 212 ± 8 million years as D1 structures are cut by plutons of the Scheelite sequence (granite of Lee Vining Canyon). D1 probably is older than 230 million years as D1 structures do not occur in the Koip sequence. The major compressional event that affected early Paleozoic rocks in this region was the mid-Paleozoic Antler orogeny. In addition, there are regional arguments for saying D1 was related to the Antler orogeny. For example, no Sonoma-age structures occur in the region south of Miller Mountain, Nevada. Hence, any pre-Jurassic structures in the region south of this area are logically assigned to the Antler orogeny. Therefore, D1 deformation probably occurred about 350 M.Y. ago during the late Devonian to early Mississippian Antler orogeny.

However, age constraints on D1 deformation in the Rush Creek sequence and the east-central Sierra as a whole are not firm and leave interpretation open to speculation. Earlier workers have suggested that first generation structures possibly formed as the result of the mid Paleozoic Antler orogeny based upon gross structural and stratigraphic similarities (Russell and Nokleberg, 1977; Brook 1977). This interpretation assumed that the orientation and style of structures that characterize the Antler orogenic belt are probably comparable to the early Sierran structures. However, Oldow (1984) has shown that Antler deformation exhibits a contrasting style and intensity between the northerly belt in north-central Nevada, which has been used to define the "Antler" structures, and the southern segment in Esmeralda and Mineral counties, Nevada, which is nearest the Sierra. In the southern segment, Antler structures are complex and contain polyphase formed structures with variable orientations. If this is the case for all of the southern part of the Antler orogenic belt then the general trends and styles of tectonic structures alone are not adequate to allow correlation between Nevada and the east-central Sierra. But since D1 structural trends are northeast trending and older than the northwest structures, the best correlation is still that they are the result of the Antler orogeny.

D2 Deformation

Distribution of D2 Structures

D2 deformation formed the most conspicuous structural features of the pendant. The orientations of F2 axial surfaces and fold hinge lines differ from those of F1 folds as shown in Plate IV. D2 structures occur in all parts of the pendant and consist of folds, cleavage, schistosity and faults of minor displacement. D2 structures are more strongly developed in western parts of the pendant. The following description of D2 structures corresponds to the progressively greater intensity of D2 structures from east to west. The Gem Lake Shear Zone, domain IV, is a special case within the Rush Creek sequence because D1 structures are no longer recognizable and F2 structures have a different style here than in domains I, II and III. Domain IV is characterized by the strongest D2 deformation and domain I the weakest deformation. The Koip sequence, domain V, has structural similarities to the Gem Lake shear zone, domain IV.

In domain III, less deformed areas are separated by highly deformed areas. These areas are planar zones of high strain where the rocks have undergone extreme flattening and characterized by transposed layering, intense cleavage and ductile shearing. Field relationships suggest that these zones were subjected to a higher degree of deformation than the surrounding areas. The evidence is discussed in the description of D2 structures under each domain where they are found. A summary of data for the high strain areas is given under faults.

Description of D2 Structures

Domain I / East Area

In domain I, F1 folds are the dominant structures and F2 structures are weakly developed. The older structures are warped by open to gentle F2 folds that have amplitudes of a 0.3 meters or less and wavelengths of 3 or more meters (fig. 22). Commonly, tight to close asymmetric anticlines between troughs of open F2 synclines have a steep east limb and show minor displacements of layers along the axial surface. Displacement is usually on the order of a few millimeters up to several centimeters. Typical bedding thickness in this domain remains relatively constant in F2 fold profiles, although thickening of calc-silicate hornfels in anticlinal hinges produces similar folds. In this area primary structures, such as local graded bedding and rare load casts, indicate tops generally face northwest.

Fig. 22 Open F2 fold is domain I, east area of the Rush Creek sequence. Bedding trends northeast and dips steeply away from the observer. Folds trend northwest, with the plunge controlled by the preexisting dip of bedding.

F2 axial surfaces trend about N 30° W and dip about 70° southwest, suggesting F2 folds are east-vergent. Vertical to steep northeast dips were also observed. Generally, F2 hingelines plunge 70 - 80° toward an azimuth of about 325° (Plate IV, diagrams B and C). A few F2 folds on the north limbs of F1 synclines, as expected, plunge to the southeast.

The superimposition of F2 minor folds on earlier F1 major folds is indicated by variably plunging F1 hingelines and curved axial surfaces. This is best observed in Unit 8 on the ridge top above the Rush Creek Trail north of Agnew Lake in domain I (Plate IV diagram C).

S2 Cleavage (domain I)

In domain I, the trend of S2 cleavage varies greatly as shown in Plate IV, diagram D. In general, the average trend of S2 cleavage is N 25° W with a dip of 80° southwest, similar to axial surfaces of F2 minor folds in this area. The variability of cleavage orientations is due in part to cleavage refraction as it passes from relatively competent to incompetent layers, and in part due to the fact that D2 deformation was weak in this domain.

Cleavage consists of parallel and closely-spaced fractures or partings separated by uncleaved rock, and is observed in some degree in all the rocks of the sequence.

Fig. 23 Northeast trending bedding is transected by northwest trending S2 cleavage. The angle of intersedtion is essentially the directional difference between D1 and D2 deformational structures, S1 and S2 respectively. Note displacement of bedding along S2 cleavage planes.

Within relatively competent siliceous rocks cleavage typically forms simple planar cracks and shows small displacements of less than 3 or 4 centimeters (fig 23).

Marble layers in Domain 1 generally do not display cleavage. The carbonate rock apparently responded ductilely during deformation and resisted the development of cleavage.

Pelitic rocks or slate appear structureless in outcrop but close examination on broken surfaces shows a very fine fissility. Thin sections show a parallel orientation of extremely fine grained mica and weak parallel arrangement of elongate minerals in the plane of S2 Cleavage. This type of cleavage is best described as incipient slaty cleavage. The more competent cherty layers locally show fairly well developed spaced cleavage, although many cherty layers in this domain do not show cleavage.

Domain II / Middle Area

The boundary between domains I and II is drawn approximately where northeast trending bedding characterizing domain I is rotated to a northwest trend by major F2 folds and where the intensity and style of minor F2 folds change. In comparison, domain I does not show strong corrugation that is common in domain II (compare Figs 22 and 24).

Fig. 24 F2 folds intensely corrugate bedding in domain II. Compare with fold in domain I, fig. 22.

The boundary between domains II and III is located along a fault that truncates and displaces the continuous units of the Rush Creek sequence (compare fig. 19 and Plate II).

The dominant D2 structure in domain II is an internally complex broad, open, asymmetric, steeply inclined anticlinal fold outlined by Units 3 and 4 on the geologic map. The east limb is overturned near the hinge area. The fold has a wavelength of about 450 meters and an amplitude of about 150 meters. It has been traced along its axial surface for a distance of about 600 meters and undoubtedly extends northwest across Tatums Hole. Due to rugged terrain to the north, tracing out this fold in future studies will be difficult. Ubiquitous F2 minor folds have axial surfaces striking about N 30° W and dipping steeply southwest about 60 - 85°. Fold hingelines plunge about 55° toward an azimuth of 310 - 330° (Plate IV diagrams G and H).

The hinge area of the anticline in domain 2 is about 150 meters across and is characterized by a complexly corrugated series of tight, inclined, asymmetric anticlines and synclines. The hinge has a box-like shape with no single apex to form the crest of the fold. The overall symmetry of the hinge is outlined by Unit 4 which defines a large scale M.

The east limb dips about 45° away from the hinge and in detail is corrugated by minor folds that are less tight than minor folds in the hinge area. The principal minor folds are open to tight, asymmetric anticlines and synclines that commonly have east limbs overturned to the east. Their style is similar to that described in domain I with fairly symmetrical open synclines and tight asymmetric anticlines. In this domain, however, the amplitude exceeds the fold wavelength and generally reflects a much greater amount of shortening. The general shape of minor folds in the east limb shows an "S" asymmetry. In this limb, northeast trending bedding that characterizes domain I is rotated progressively from northeast to eastwest to northwest with a dip change from an original 60° northwest to vertical to southwest (overturned steeply east). Bedding rotates back to a normal northwest dip in the hinge area (Plate IV diagram F).

F1 hingelines are folded by this large scale F2 fold and the result is a change in plunge from southwest to northeast. This can be observed by comparing diagrams C and H, Plate IV.

The west limb of the anticline dips about 30° away from the hinge and is also corrugated by minor F2 folds that generally are tighter than folds in the east limb. The principal minor folds are tight to uncommonly isoclinal, steeply inclined to the east, asymmetric anticlines and synclines with a general "Z" asymmetry.

Hingelines of F2 minor folds are nearly parallel throughout the anticline and trend northwest (Plate IV diagram G and H). A few isoclinal to tight folds having a northerly trend are located in close proximity to northwest trending faults. The faults appear to be related to D2 deformation as indicated by displacement of F2 axial surfaces generally parallel to fault planes.

The west limb of the anticline is truncated by a northwest trending, steeply inclined high strain zone. In addition, a post D2 brittle fault cuts through the high strain area as well. The high strain zone, however bends northeast while the younger fault trends northwest and cuts the less deformed strata. Across this fault Units 3 and 4 show an apparent offset of about 180 meters. D2 structures have intensely deformed the rocks in the vicinity of this fault. Along this fault F2 folds are tighter than in the rest of the domain and commonly are truncated and dismembered. Folds also tend to have a more northerly trend in close proximity to the fault than other F2 folds in the pendant. This feature is the boundary between domains II and III.

<u>S2 Cleavage (domain II)</u>

In domain II, the trend of S2 cleavage averages N 38° W with a dip of 76° southwest (Plate IV diagram I). This is similar to the orientation of axial surfaces of minor F2 folds in this area (compare diagrams G and I, Plate IV). As in domain I, S2 cleavage is a spaced cleavage although it is markedly stronger in domain II. Competent layers show a pervasive spaced cleavage and commonly are displaced up to several centimeters by slip on the cleavage planes (fig. 25).

Locally, the hinge areas of larger F2 folds show intense slaty cleavage and appear to be faulted. Many of these have displacements of less than a meter, but a few have displacements of up to 15 meters.

The hinge areas of larger F2 folds are difficult to study because they are mostly exposed in steep terrain. In addition, igneous dikes in many cases intruded the hinge areas of large F2 folds and have masked the structural relationships. Because of these problems a full understanding of faulting within the axial surfaces of major F2 folds was not attained.

Domain III / West Area

This western area of the Rush Creek sequence is the most problematic, making correlation with the known stratigraphy to the east difficult. Whereas domains I and II are characterized by uniform and continuous layering and fairly complete exposures, domain III is characterized by intense D2 deformation, high strain zones, discontinuous

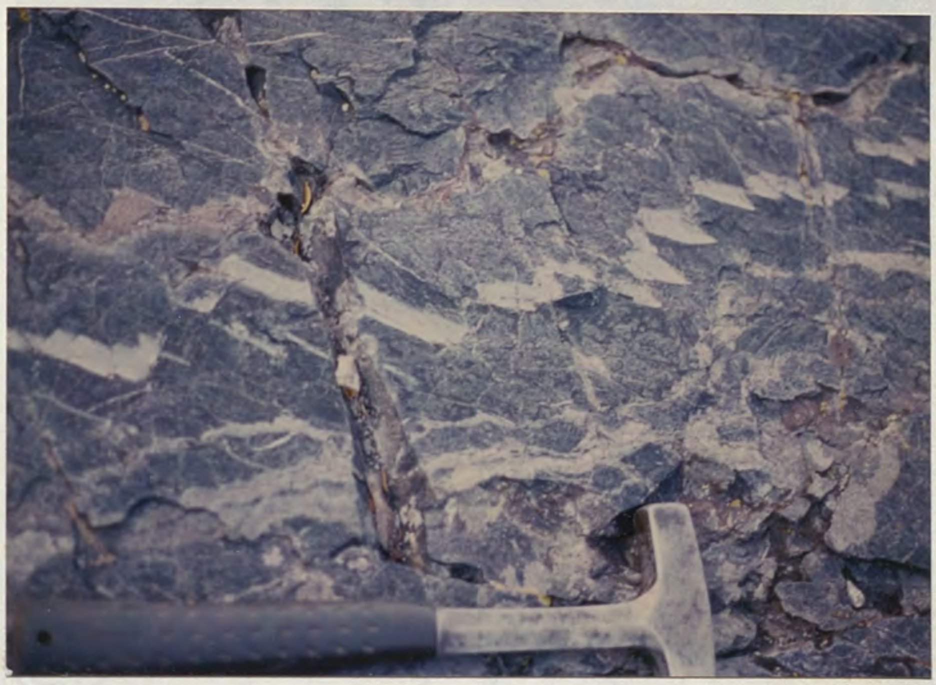

Fig. 25 S2 spaced cleavage showing displacement along phosphatic layer in chert. Location in Unit 3, domain II, Rush Creek sequence. Compare with weakly developed cleavage in domain I, fig. 16.

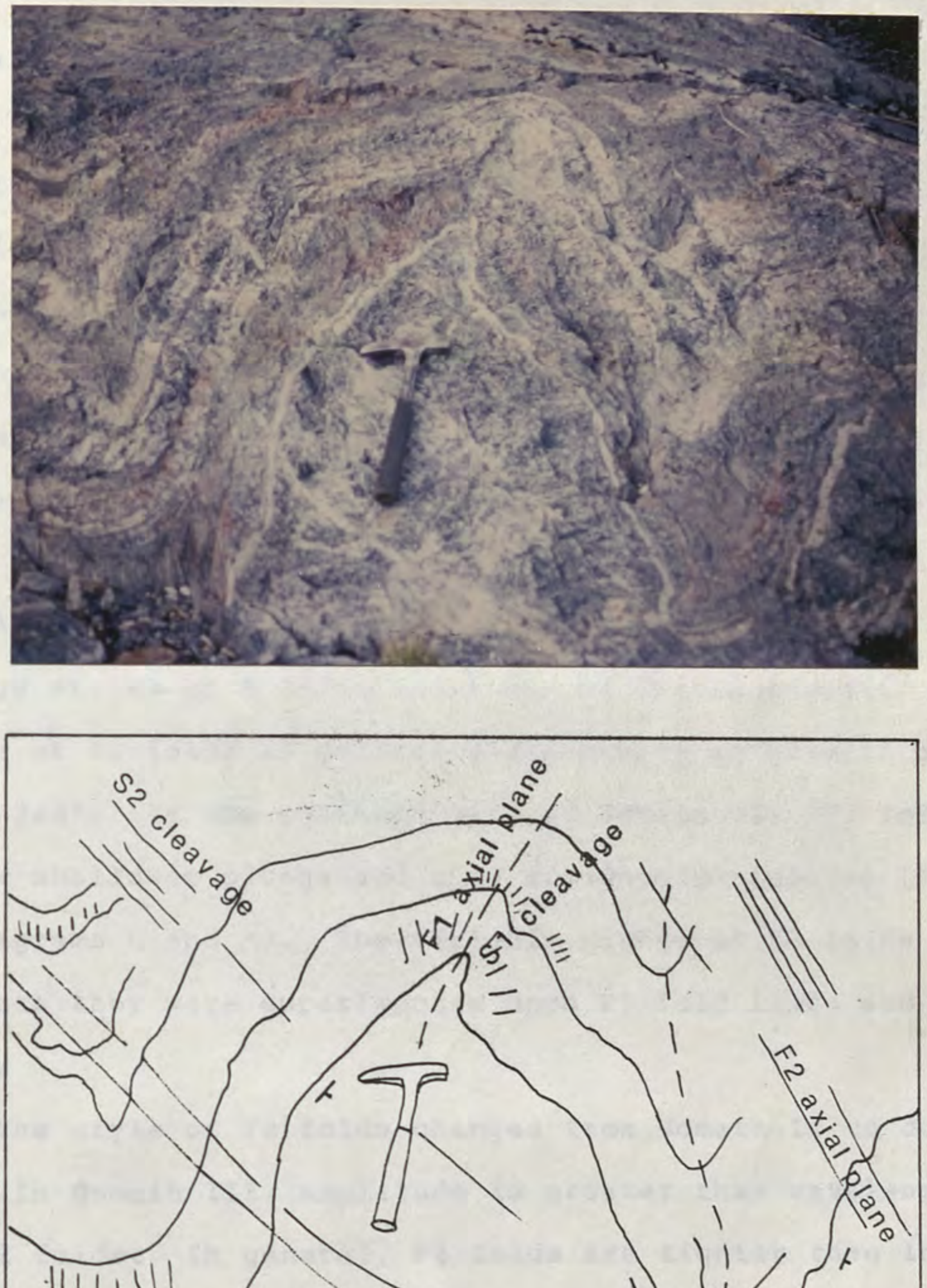

Fig. 26 F1 fold in phosphatic chert is superimposed by F2 folds and S2 cleavages. View facing north. Outcrop is located below Gem Lake dam.

strata, and incomplete exposures. With these problems in mind, the rocks in domain III are tentatively correlated with the continuous and uniform stratigraphy of domains I and II.

As described previously, domain III is bounded on the east by a major fault that separates this domain from the continuous and uniform stratigraphy of domains I and II. Domain III is bordered on the west by the Gem Lake shear zone. The width of the domain is about 480 meters.

Axial surfaces of F2 folds in domain III have an average strike of N 38° W and a dip of 78° southwest. The plunge of F2 folds is generally steep with an azimuth of about 322°. In the southern part of domain III, F2 folds have a shallower plunge and some are doubly plunging (Plate IV diagrams L and M). The variable plunge of F2 folds suggests they were superimposed upon F1 fold limbs and hinge areas.

The style of F2 folds changes from domain II to domain III. In domain III, amplitude is greater than wavelength for F2 folds. In general, F2 folds are tighter than in domain II. This suggests that domain III has undergone a greater amount of shortening than the domains to the east. A typical F2 style fold is shown in figure 27 (compare figures 22 and 27).

Fig. 27 Typical "Nevadan" F2 fold profile in siliceous rocks marked by an open syncline and a tight anticline. Fold trends about N 30 W, 80 southwest and plunges 60 northwest. Located in less deformed area of domain III.

The dominant F2 structure in domain III is an apparent large-scale syncline. It should be noted that the structure is inferred by isolated outcrops that are divided by high strain areas. Nonetheless, the stratigraphy in the less deformed areas support the structural interpretation and it is assumed that the high strain areas dissected this syncline possibly in response to high strain during the later stages of folding.

The syncline is tight to close, asymmetric, overturned to the east and outlined by discontinuous outcrops of Units 3, 4 and 5. The fold has an exposed breadth of about 240 meters and an amplitude of at least 500 meters. Like the anticline in domain II it probably extends northwest for a considerable distance. The east limb of the syncline was possibly connected to the anticline in domain II prior to faulting.

Other major F2 structures are not as well exposed, although apparent pieces of large scale folds are expressed by asymmetry of minor fold trains and folded contacts. Above Gem Lake dam, a thick calc-silicate hornfels unit tentatively assigned to Unit 4 forms the core of a northwest trending F2 anticline. The hinge area is 90 meters wide and is exposed along the Rush Creek trail where bedding planes dip away from a strongly corrugated hinge. Parasitic folds have long limbs measuring tens of meters in some cases with tight kink like hinges. The anticline is overturned to the east and at a distance from the hinge the limbs are nearly parallel to the axial surface. The consistent westward dip of the axial surfaces suggest an eastward vergence.

Directly below Gem Lake dam a massive sandy marble unit interbedded with thick chert subunits appears to be a intensely deformed remnant of Unit 5. Good exposures along Rush Creek, 150 meters below the dam, show the unit is strongly corrugated by wavetrains of F2 folds. F1 folds are also present in this area, judging from the doubly plunging F2 folds described previously. The lithologic association of Unit 5 and an underlying calc-silicate, possibly unit 4, suggest the major structure is a corrugated syncline.

Within domain III, northwest trending planar zones of high strain, varying in width from 5 to 20 meters, contain much stronger D2 deformation than in the surrounding rock. In these zones bedding or layering is transposed parallel to S2 cleavage. Limbs of F2 folds are either sheared or very long limbed. The folds trend northwest and plunge near vertical to steeply northwest. Stretching lineations are parallel to F2 hingelines. The hinge areas of F2 folds in the high strain zones are commonly compressed and extended parallel to S2 (fig. 28). Marble layers in these zones of high strain are discontinuous, boudinaged, and show intense flowage (fig. 29). These zones of high strain commonly border calc-silicate hornfels. This lithology remained competent during deformation while chert and marble responded in an incompetent fashion. The high strain zones curve around these calcsilicate bodies forming large scale boudin. In general the planar zones of high strain divide more coherent strata and structures in domain III and the coherent strata is generally made up of calc-silicate rocks.

Much of domain III has large scale, tight to isoclinal folds with the predominant orientation of bedding in high strain areas northwesterly, approximately parallel to the axial surface of F2 folds. This is characteristic of transposition layering as outlined by Hobbs and others (1976, fig. 5.29, p. 253). In general, the F2 folds are extremely long limbed with most of the relict bedding parallel to the regional northwest structural grain. There is little variation in the orientation of bedding along the fold limbs, although in the hinge areas, relict northeast trending bedding planes are preserved. Evidence that the bedding was originally northeast trending suggests that prior to F2 deformation, uniform and continuous units of domains I and II extended into domain III.

<u>S2 Cleavage (domain III)</u>

The trend of S2 cleavage in domain III is N 38° W with a dip of 70° southwest. This orientation is similar to axial surfaces of minor F2 fold in this area (see plate IV, compare diagrams L and N).

Fig. 28 Tight F2 fold becoming isoclinal in the hinge area. Located in high strain area of domain II.

Fig. 29 Interbedded marble layer in cherty rocks is almost obliterated with remnant marble found as boudins. Located in high strain area of domain III below Gem Lake dam.

S2 is a well-developed spaced cleavage in cherty layers and is locally an intense slaty cleavage. Minor displacement in the axial surfaces of F2 folds suggests flattening was accompanied by simple shear during deformation. Calc-silicate layers responded competently during deformation and consistently show less intense cleavage than cherty siliceous rocks. Pelitic rocks consistently display intense slaty cleavage. Carbonate rocks in domain III have a much stronger cleavage than in the eastern areas and typically have curved cleavage planes produced by ductile flow during deformation (fig. 30). The massive marble layers responded ductilely and have lost all sedimentary character. Some of the marble outcrops resemble a light colored, fissile shaly rock (fig. 31). Interbedded cherty layers are strongly folded and give hints of the amount of flattening that took place as figure 30 exemplifies. Generally, cleavage is much more pervasive and well-developed in the western part of the Rush Creek sequence and most intense in zones of high strain.

Gem Lake shear zone / Domain IV

The Gem Lake shear zone, domain IV, is a sequence of highly deformed and mylonitic rocks marking a ductile shear zone between the Rush Creek and Koip sequences. The area is the strongest deformed domain of D2 deformation in the study

Fig. 30 In intensely deformed rock the cherty layer has remained competent and relict bedding is preserved (dark folded layer). The marble layers do not retain any relict bedding and show strongly developed flow cleavage axial planar to F2 folds.

Fig. 31 Sandy marble shows pervasive slaty cleavage in domain III, western part of the Rush Creek sequence.

area and the structure is similar to the high strain areas in domain III. The shear zone is a narrow, planar zone about 100 meters wide at the south side of Gem Lake and thickens to about 280 meters north of Gem Lake. Reinterpretation of descriptions from Kistler (1960, 1966b) and Huber and Rinehart (1965) suggests that the shear zone extends both north and south a considerable distance.

Mylonitic fabric is confined to the shear zone and the intensity of deformation decreases eastward, away from the contact with the Koip sequence. The shear zone trends northwest and has a down dip stretching lineation that dominantly plunges steeply northwest but commonly is near vertical. The fabric in the shear zone is localized regular foliation, planer layering and intense crenulation cleavage. Large F2 folds are tight to isoclinal and commonly only the hinge area is preserved and the limbs are sheared out (fig 32). Small intrafolial isoclinal folds are less common (fig. 33). Where preserved, relict bedding in the Gem Lake shear zone is completely transposed parallel to the main phase slaty cleavage and the regional structural grain for D2 deformation.

Mylonitic chert has very thin, laminar layering (fig. 34). Some elongate, lighter layers in the chert taper and pinch out in the plane of S2. Stretching lineations are parallel to hinge lines of F2 folds and are steeply dipping

Fig. 32 F2 fold is cherty rocks is sheared by highly foliated layers parallel to S2, domain IV, Gem Lake shear zone.

Fig. 33 Isoclinal intrafolial folds form within intensely foliated cherty rocks parallel to S2. Note F2 late phase folds deform main phase S2 cleavage, Gem Lake shear zone, domain IV.

Fig. 34 A very laminar mylonitic chert, domain IV, Gem Lake shear zone.

to nearly vertical. The general pattern for hingelines and lineations in the Rush Creek sequence is that they progressivly steepen from east to west and are steepest in the shear zone. Silty and impure quartz rich rocks generally have a very regular foliation.

In the Gem Lake shear zone, D2 deformation is characterized by two phases of structures and D1 structures are not present. First formed D2 structures or main phase structures are marked by a penetrative, slaty to phyllitic cleavage (S2) with an average strike of N 34° W and a dip of 84° southwest (Plate IV diagram S). Main phase folds are not common, but a few minor folds occur in cherty layers near the north shore of Gem Lake. These folds are small, tight, and plunge 85° toward an azimuth of 320°, and have an axial surface cleavage trending N 40° W and dipping 80° southwest. This is also the general trend of stretching lineations.

Late phase structures occur in discrete domains and are absent in others. These structural domains are controlled in part by lithology; thinly-layered marble is the principal unit that shows the strong late phase structures (fig. 35). For the most part, chert, siltstone, and other rocks lacking marble do not exhibit late phase structures.

Late phase D2 structures are marked by a strong crenulation cleavage, small scale folds, conjugate folds and kinks (S3) (fig. 35 and 36).

Fig. 35 Intensely foliated marble and interbedded chert shows an irregular crenulation defined as small scale folds ranging from "kink-like" folds with angular hinges to rounded forms. Folds deforms northwest trending S2 slaty cleavage. Located on the northside of Gem Lake, domain IV, Gem Lake shear zone.

Fig 36 Conjugate or box fold in intensely foliated chert deforms N 30 W trending slaty cleavage. Right axial plane (yellow pencil) trends N 53 W, vertical, and left axial plane (blue pen) trends N 45 E, vertical. Fold is interpreted as forming at the intersection of conjugate kink bands. Located north of Gem Lake, domain IV, Gem Lake shear zone.

Plate IV, diagrams P through T show the general trace of S2 and S3. The late phase folds and crenulations have axial planes that are divergent from the main phase slaty cleavage and associated main phase fold axial surfaces. A westerly set has an average strike of N 56° W and dips 80° southwest. An easterly set has an average strike of N 34° E and dips 74° southeast (see plate IV, diagram Q). These late phase structures deformed the main phase slaty cleavage and mylonitic foliation. Tobisch and Fiske (1976) used the term "Gem Lake deformation" for especially well-developed late phase structures on the south side of Gem Lake.

<u>Shear zone Associations and regional comparisons</u>

The data from this study indicate that the intensity of D2 structures may be directly related to large scale D2 shear zones (high strain areas). For example, data reported here shows that the intensity of D2 deformation (strain related to shortening) in the Rush Creek sequence increases from east to west and culminates at the Gem Lake shear zone. In contrast, the opposite strain relationship is reported in the Koip sequence. Tobisch and Fiske (1982, fig 10, p. 190) showed a progressive increase in shortening in the Koip sequence from west to east from the interior of the metavolcanic rocks to the Paleozoic rocks on the east. The Paleozoic rocks they described in the Devils Postpile quadrangle are probably an extension of the Gem Lake shear zone, although they did not identify the Paleozoic rocks as a shear zone. They did suggest that on a regional basis it is very likely that there has been tectonic movement between the Paleozoic and Mesozoic rocks. On the west side of the Ritter Range pendant, Tobisch and Fiske (1982) identified a narrow shear zone and showed a progressive increase in tectonic shortening from east to west towards that shear zone. Hence it appears that strain or shortening related to D2 deformation increases towards and culminates at high strain areas that are interpreted herein as ductile shear zones. Figure 37 illustrates this point.

Koip sequence / Domain V

The orientations of structures in the Koip sequence are the same as those in the Gem Lake Sequence (compare diagrams for domains IV and V, Plate IV). The dominant S2 main phase cleavage has an average strike of N 24° W and dips 80° southwest. F2 folds exhibit an axial surface schistosity parallel to S2 main phase foliation. A northwest-plunging mineral and clast alignment is developed parallel to the main phase slaty cleavage and is similar in orientation to the stretching lineations in the Gem Lake shear zone.

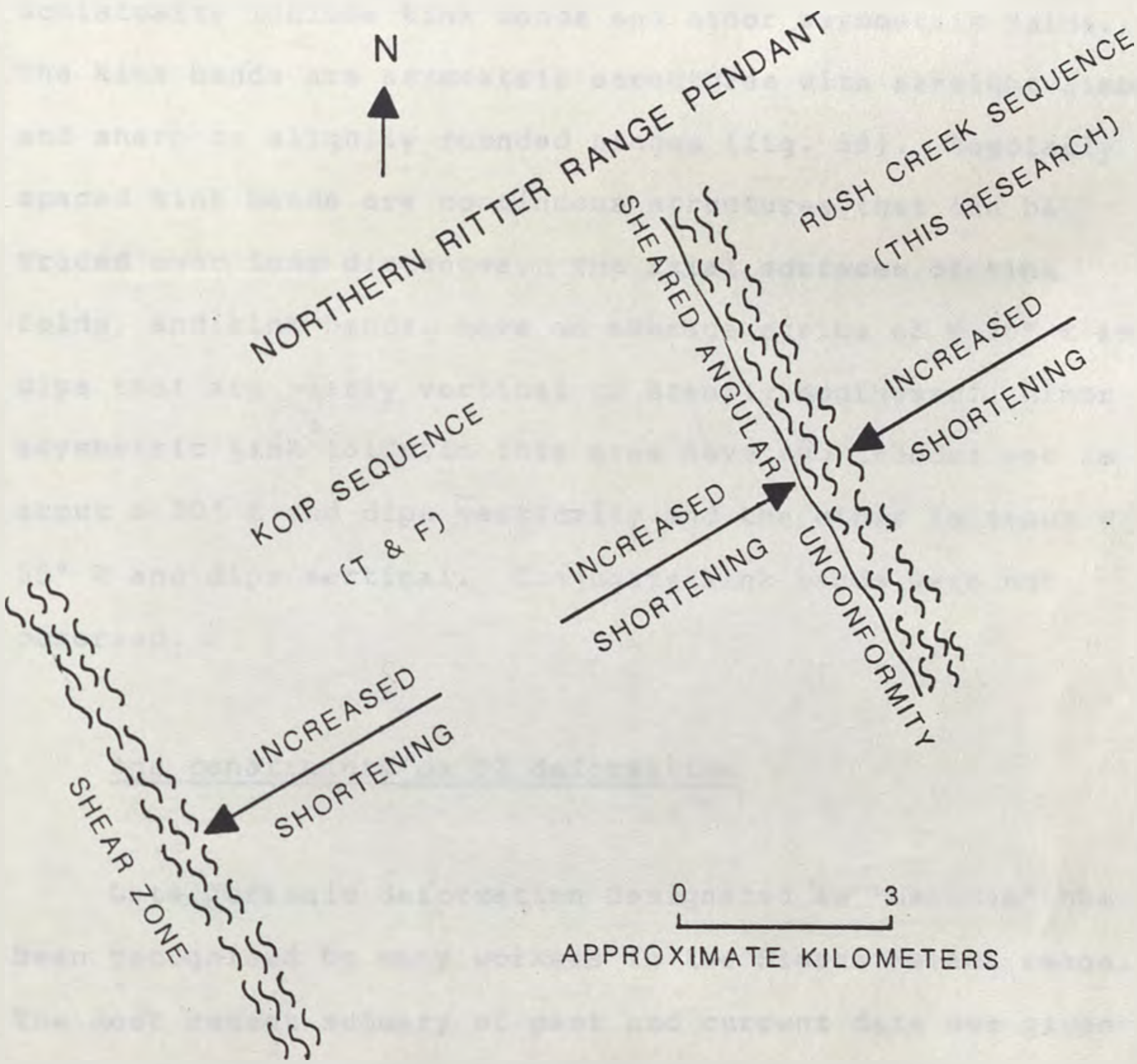

Fig. 37 Sketch map of the Northern Ritter Range pendant showing relative shortening in relation to deformation forming northwest trending structures. Arrows show direction of increasing strain along northwest trending folds and cleavages. Koip sequence studied by Tobisch and Fiske (1982) and Paleozoic rocks this research.

Late phase F2 structures that deform the main phase schistosity include kink bands and minor asymmetric folds. The kink bands are asymmetric structures with straight limbs and sharp to slightly rounded hinges (fig. 38). Regularly spaced kink bands are continuous structures that can be traced over long distances. The axial surfaces of kink folds, and kink bands, have an average strike of N 30° E and dips that are nearly vertical to steeply southeast. Minor asymmetric kink folds in this area have two trends; one is about N 30° E and dips vertically and the other is about N 55° W and dips vertical. Conjugate kink bands were not observed.

Age constraints on D2 deformation

Late Jurassic deformation designated as "Nevadan" has been recognised by many workers in the Sierra Nevada range. The most recent summary of past and current data was given by Schweickert and others (1984).

The traditional view is that Nevadan structures are represented by northwest-trending slaty cleavages and tight folds which were formed throughout the extent of the Sierra Nevada during a shortlived event in the Late Jurassic. In this interpretation the D2 structures described here are Nevadan structures. A late phase of structures that deform the main phase structures was also interpreted as having

Fig. 38 Typical foliated wacke of the Koip sequence is displaced by kink bands. Trend of foliation is about N 30 W and is parallel to main phase slaty cleavage.

formed during the Nevadan orogeny (Schweickert and others, 1984). Tobisch and Fiske (1976) suggested that late phase structures in the Rush Creek drainage formed during the Late Jurassic Nevadan orogeny.

A departure from the traditional view of northwest trending structures in the eastern Sierra was put forth by Tobisch and Fiske (1982) from data in the Ritter Range pendant just southwest of the study area. They suggested that northwest-trending structures previously interpreted as "Nevadan", are actually the result of at least two and possibly three successive, parallel deformations that were separated by a substantial period of geologic time. Tobisch and Fiske also argued that Cretaceous deformation produced northwest-trending cleavage and folds that are indistinguishable from those which formed during the Late Jurassic, based upon unpublished isotopic ages for rocks from the Ritter Range pendant. But because this region has been subjected to multiple episodes of regional and thermal metamorphism there is a strong possibility that the radiometric clock has been reset by post formation heating, and the ages are too young.

Nokleberg and Kistler (1980) also suggested northwest-trending structures did not form exclusively during the Late Jurassic Nevadan orogeny. Instead, they asserted that coaxial multiple deformations with this trend possibly formed during the Triassic, Late Jurassic, and middle Cretaceous. Additionally, late phase structures that Tobisch and Fiske (1976) presumed to have formed during the Late Jurassic have been suggested by Nokleberg and Kistler (1980) to have formed during the middle to late Cretaceous.

These interpretations cast doubt that the structures assigned in this study to D2 deformation were formed in the Late Jurassic Nevadan orogeny. However, since it was not possible to establish an absolute date for D2 structures described in this study, and since no evidence of multiple parallel deformations was observed, the traditional view has been followed. Thus D2 structures described here are considered to have formed during the Late Jurassic Nevadan orogeny.

Faults

Faults in the Rush Creek drainage fall into three categories (1) Post D2 brittle faults, (2) D2 northwest trending faults axial planar to F2 folds and (3) high strain areas interpreted to be ductile shear zones.

Brittle faults in the Rush Creek Drainage vary in strike from northwest to northeast. Locally, slickensides indicate oblique movement along nearly vertical planes. In most cases these faults are marked by steep narrow ravines and are accompanied by igneous intrusions. Movement appears to have occurred both prior to and after emplacement of the dikes, suggesting the fault zones were intermittently active. Displacement varies between a few meters up to a dozen meters. These faults generally form normal faults.

Many northwest faults were synchronous with D2 deformation as indicated by a parallel relationship between axial surfaces of F2 folds. Most displacements on axial surfaces with this geometry are generally less than a meter but the largest is about 15 meters. These faults generally form reverse faults. Kistler (1966b, p. E18) also noted northwest-trending faults parallel F2 axial surfaces and suggested this reflects extreme strain during the deformation that produced the folding.

One fault does not fall into the above categories. In the northeast corner of the study area an apparent left lateral fault truncates the metamorphic rocks with apparent displacement of 280 meters. The fault is marked by intense D2 deformation, discordance of strata, S2 foliation, dismembered structures and by steep cliffs at the east end of Tatum's Hole. The displaced strata on the northeast side of the fault were briefly examined and appear to be units 5,6,7, and 8 of the Rush Creek sequence. The fault forms a lineament with an east-west trend in the Rush Creek drainage and curves northward through the ridge north of Tatum's Hole (see Plate 1, Geologic Map).

In the intensely deformed parts of the Rush Creek sequence, areas of high strain are possibly traces of thrust faults. Field evidence for the high strain areas includes transposed layering, intense slaty cleavage, truncated strata and localized intense folding. These zones of high strain have been diagrammatically drawn on the cross section B to B', plate II. These high strain areas form roughly planar zones that have a general orientation parallel to D2 deformation structures. However, in the northwest corner of domain II, fragmentary evidence suggests that part of the fault trace trends parallel to D1 deformation structures. The following discussion sights the evidence for thrust faults.

The Gem Lake shear zone was described earlier in the text as a sequence of highly deformed and mylonitic rocks. The high strain areas in domain III fall under this description although the fabric does not contain a late phase crenulation common in the Gem Lake shear zone. The mylonitic fabric in the high strain areas has very thin, laminar layering that taper and pinch out. In places this laminar layering curves around less deformed strata. These more coherent areas form large scale boudinage (see plate II, Interpretive Map). In one locality between domain II and III northwest laminar layering truncates northeast laminar layering. The northeast laminar layering is parallel to D1 structures and might be the remnants of a D1 ductile fault.

The rocks in domain III are similar to those in the uniform and continuous domains to the east but direct correlation was not possible. This was due to the dismemberment of domain III by the high strain areas.

Interpretation of the high strain areas must take into account the ductile layering, truncated strata, large scale boudinage and dismembered strata. A plausible interpretation is that the structures formed as ductile shear zones during thrust faulting. Although differences are noted, these structures are similar to those that identify imbricated thrust faults. Oldow (1984) described similar structures for the Roberts Mountains Allochthon in the Miller Mountain-Candelaria Hills area in west-central Nevada. It is also important to note that the rocks in the allochthon are descriptively very similar to those in the Rush Creek drainage.

Oldow (1984) and others have used the orientation of folds to determine the direction of thrust transport. Using this interpretation, northeast trending D1 folds are inferred as being genetically related to emplacement of the Roberts Mountains allochthon and Antler age thrusting and indicates a south easterly transport. Northwest trending D2 folds are inferred as being genetically related to Nevadan age thrusts and indicates a northeast transport.

Further detailed work is required to determine the exact nature of these high strain zones.

Structures in the granite of Lee Vining Canyon

The granitic rock within the Rush Creek drainage contains a spaced cleavage that trends about N 30-50° W and dips vertical to steeply east or west. The cleavage has irregular spacing from 3 mm apart to 1-2 cm apart. Some cleavage planes have striations or slickensides indicating displacement. At one outcrop 550 meters northeast of Agnew Lake dam a cleavage trends N 40° W and dips steeply east with striations that trend N 52° E, 65 northeast on the cleavage plane.

In the same area a ductile shear zone trends about N 35° W and dips vertical to steeply east or west. The ductile shear zone was traced for at least 50 meters and probably extends for a considerable distance. The shear zone is about 0.3 to 0.6 meters thick and exhibits pinch-and-swell structures and incipient boudinage. The shear zone is strongly foliated, dark gray and has stretched clasts of relict granite fragments and quartz. Granitic rock shows sub-parallel cleavage and foliation along the shear zone.

The trends of the these structures in the granite are similar to those that formed in the metasedimentary rocks during D2 deformation therefore the structures in the granite are interpreted to have formed during that deformation.

Joints

A regional joint set occurs in the granite of Lee Vining Canyon. During this project the joints were not studied systematically but the following general observations were made.

(1) A conjugate system of northeast and northwest-trending joint sets cuts both the granitic and metamorphic rocks.
(2) The trend of the northwest set is similar to that of faults and S2 cleavage in the metamorphic rocks suggesting the joints are related to D2 structures .
(3) The joint pattern appears to refract as it enters the metamorphic rocks, producing a slightly more westerly trend in those rocks.
(4) Post-D2 porphyry dikes were emplaced along the joint system in both the granitic and metamorphic rocks.

In the metamorphic rocks alteration along the joints is marked by a bleached zone. The alteration is possibly a product of hydrothermal fluids using the joint systems as a conduit during emplacement of post D2 dikes. Along the joints, later brittle faults further disrupt the rock.

PROBABLE AGE	DEFORMATIONAL EVENT	AVERAGE TREND	PLANAR STRUCTURE	STRUCTURES FORMED	DEFORMATIONAL STYLE
MID PALEOZOIC	D1 ANTLER OROGENY	N30-40E	S1	LARGE-SCALE, SW VERGING SYNCLINE WITH DEVELOPMENT OF NORTHEAST TRENDING UPRIGHT TO INCLINED SMALLER SCALE SYNCLINES AND ANTICLINES.	FIRST PHASE OF FOLDING OF PREVIOUSLY UNDEFORMED MIOGEOCLINAL SEDIMENTARY ROCKS. SOUTHEAST DIRECTED THRUSTING (?).
LATE JURASSIC (155 $\pm$3MY)	$D2_A$ MAIN PHASE NEVADAN OROGENY	N30W	S2	LARGE-SCALE NORTHEAST VERGING, NORTHWEST TRENDING, UBIQUITOUS ASYMMETRIC SYNCLINES AND ANTICLINES WITH ASSOCIATED CLEAVAGE. EAST TO WEST INCREASE INTENSITY OF DEFORMATION INDICATED BY TIGHTENING OF FOLDS AND INCREASE DEVELOPMENT OF CLEAVAGE.	NORTHWEST TRENDING FOLDS AND CLEAVAGES SUPERIMPOSED OVER OLDER NORTHEAST TRENDING F1 FOLDS. NORTHEAST DIRECTED THRUSTING (?) AND DEVELOPMENT OF SHEAR ZONES AND HIGH STRAIN AREAS. STUCTURAL DEVELOPMENT INREASES TOWARDS AND CULMINATES AT SHEAR ZONES.
LATE JURASSIC	$D2_B$ LATE PHASE NEVADAN OROGENY	N56W N34E	S3	STRONG CRENULATION CLEAVAGE, SMALL-SCALE ASYMMETRIC FOLDS, KINKS, AND KINK BANDS.	DOMAINAL DISTRIBUTION OF INTENSE CRENULATIONS AND SMALL-SCALE KINK LIKE FOLDS SUPERIMPOSED OVER MAIN PHASE SLATY CLEAVAGE.

FIG. 39 SUMMARY OF STRUCTURAL DEVELOPMENT

GEOLOGIC HISTORY

Early Paleozoic Deposition

The geologic history of the Rush Creek sequence began with deposition of marine sediments in the early Paleozoic. The extremely fine-grained and well-bedded strata were probably deposited in a low-energy environment in open water of the outer shelf. A minimum of 820 meters of sediments was deposited without a major break in deposition. As pointed out by Stewart (1980) such rocks formed along a northeast trending passive margin that existed in Nevada and eastern California until the end of the Devonian. Possibly correlative units are the Ordovician Palmetto Formation and the Upper Cambrian Emigrant Formation in Esmeralda County, Nevada.

Prior to the Antler orogeny, mafic dikes intruded the sediments possibly as a precursor to mid Paleozoic deformation.

Antler Orogeny (D1 deformation)

The mid-Paleozoic Antler orogeny brought the onset of F1 folding and southeast directed thrusting (?) and the end of deposition of the Rush Creek sequence. The average N 40° E strike for D1 structures is similar to the orientation of Antler structures reported in Nevada (Burchfiel and Davis, 1972; Oldow 1984).

The intense folding and faulting that characterizes the Antler orogenic belt culminated in the Early Mississippian in the emplacement of the Roberts Mountains allochthon. The northeast trend of F1 axial surfaces is in agreement with a southeast vergence proposed for this thrust. An important question has to do with the structural position of the rocks described here relative to the Roberts Mountains thrust. Rocks of the transitional assemblage in north-central Nevada are autochthonous and parautochthonous and were overridden by the Roberts Mountains thrust (Schweickert and Snyder, 1981). Since rocks in the Rush Creek sequence resemble the transitional assemblage, they are probably in the lower plate.

Sonoma Orogeny

The Sonoma Orogeny was the next regional tectonic event occurring in the Late Permian and Early Triassic time.

Silberling and Roberts (1962) defined the Sonoma orogeny as a major tectonic event in Nevada involving widespread thrusting and emplacement of the Golconda allochthon. During the Sonoma orogeny areas in present day eastern California and Nevada including the field area may have formed a structural high, marked by uplift and erosion (Kistler 1966b, Brook and others, 1974, and others). This probably resulted in the uplift and erosion of the Rush Creek sequence.

Post Sonoma Orogeny

After the Sonoma Orogeny and during the Early to Middle Triassic, the northeast-trending Paleozoic miogeocline was obliquely truncated by rifting or large scale strike-slip faulting. This initiated a northwest trending subduction zone and a subsequent Andean-type magmatic arc (Burchfiel and Davis, 1972; Schweickert, 1976, 1981 and others). Along this northwest-trending margin of the continent, volcanic and sedimentary rocks of the Koip sequence were deposited in angular unconformity upon rocks of the Rush Creek sequence. At about the same time, the granite of Lee Vining Canyon was emplaced into the deformed rocks of the Rush Creek sequence. The latest stage of igneous activity was the intrusion of pre-F2 granitic and porphyritic dikes and sills.

Nevadan Orogeny

The major tectonic event that established the northwest-trending structural grain of the region was the Late Jurassic Nevadan orogeny (Bateman and Clark, 1974; Schweickert, 1978; Kistler and Nokleberg, 1980; Schweickert and others, 1984). D2 structures that formed during the Nevadan orogeny were superimposed upon the pre-existing D1 structures in the Rush Creek sequence.

The Nevadan orogeny has been proposed to have occurred during a collisional event about 153-155 m.y. ago (Schweickert and Cowan, 1975; Schweickert and others, 1984). This involved the west-facing Triassic-Jurassic marginal arc represented by the Koip sequence and granite of Lee Vining Canyon and other plutons. D2 (Nevadan) deformation occurred when an opposing, east facing oceanic arc-trench system collided with this marginal arc and was partially subducted. Subsequently intense crustal shorting during the collision formed a broad synclinorium with rocks of the preexisting marginal arc in its keel (Bateman and Clark, 1974; Schweickert, 1978; Schweickert and others, 1984). The inferred axial-surface trace of the Nevadan synclinorium lies 10-20 Km west of this part of the Rush Creek drainage. During the development of this structure, Paleozoic strata and Pre-Nevadan structures were folded and thrusted (?) and subsequently rotated to their present trends. Deformation was inhomogeneous, with ductile shear zones separating less deformed domains.

Post Nevadan Orogeny

After the Nevadan Orogeny the region was engulfed by Cretaceous granitic rocks of the Sierra Nevada batholith. Dikes and sills intruded the metamorphic rocks sometime after the Nevadan orogeny.

SUMMARY AND CONCLUSION

The Rush Creek drainage is one of the few areas in the east-central Sierra that contain a relatively intact sequence of lower Paleozoic strata. Results of the detailed study of this sequence are outlined below.

(1) The Rush Creek sequence consists of well bedded, metamorphosed equivalents of fine-grained, quartz rich argillite, chert, impure limestone/dolomite, limestone/dolomite and minor quartzite of probably early Paleozoic age and tentatively correlated with the lower part of the Palmetto Formation and upper part of the Cambrian Emigrant Formation in Esmeralda County, Nevada.

(2) The first recognition of phosphatic chert in the Northern Ritter Range pendant.

(3) The Gem lake shear zone makes up the western part of the Rush Creek sequence and forms the boundary with the overlying Mesozoic Koip sequence.

(4) The first recognition of northeast-trending F1 folds. F1 folds are the oldest structures observed and are possibly genetically related to thrusting during the mid-Paleozoic Antler orogeny.

(5) The Rush Creek sequence exhibits D1 structures but the

Koip Sequence does not.

(6) Northwest-trending folds probably formed during the Late Jurassic Nevadan orogeny. F2 folds and cleavage show a progressive increase in development from east to west exhibited by the tightening of folds and progressively more intense development of cleavage.

(7) The intensity of D2 deformation increases towards and culminates at ductile shear zones such as the Gem Lake shear zone. Planar zones of high strain possibly indicate D2 deformation caused by northeast directed thrusting.

(8) D2 deformation is characterized by an initial main phase of structures that are deformed by late phase structures.

(9) D2 late phase structures in the Gem Lake shear zone developed in local domains and controled by the rock type.

The results of this study and comparison with Kistler (1960) suggest the structural framework and stratigraphy that characterize the Rush Creek sequence also are present in the Gull Lake pendant 3 km to the east thus linking these rocks. This disputes the conclusion of Nokleberg (1983) that these rocks are separated by a major thrust fault representing a tectonic suture between accreted tectonostratigraphic terranes of upper and lower Paleozoic rocks.

Several problems remain unresolved. No fossils were found and the absolute age of the Rush Creek sequence is not known. Their ages have been inferred from lithologic and structural relationships. The exact nature of the contact between the Rush Creek sequence and the Koip sequence is not resolved and the structural picture is not complete.

I believe additional mapping in areas north and south of the Rush Creek drainage will solve these problems.

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